YOLO BYPASS SALMON BENEFITS MODEL:
MODELING THE BENEFITS OF YOLO BYPASS RESTORATION ACTIONS ON CHINOOK SALMON

Model Documentation, Alternatives Analysis, and Effects Analysis

Prepared for:

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EXECUTIVE SUMMARY

The Yolo Bypass Salmonid Habitat Restoration and Fish Passage Draft Implementation Plan (Implementation Plan) was prepared to evaluate the potential to restore floodplain rearing habitat through increased seasonal inundation within the lower Sacramento River basin, and reduce migratory delays and loss of salmon, steelhead, and sturgeon, through the modification of Fremont Weir and other structures of the Yolo Bypass. Prior to Implementation Plan execution, potential benefits of restoration actions on all four CV Chinook salmon runs are to be evaluated quantitatively through a targeted modeling effort.

The Yolo Bypass Chinook Salmon Benefits Model (SBM) is a mechanistic, deterministic simulation model that quantifies potential benefits of Yolo Bypass restoration actions on CV Chinook salmon runs that spawn upstream of the Yolo Bypass. Five key benefit measurements were identified: juvenile (1) survival, (2) size, (3) size variability, and (4) timing variability at entrance to the marine environment (Chipps Island) and (5) adult returns (escapement). Using the SBM, we quantified lifestage-specific and cumulative impacts of restoration actions on each Chinook salmon run and compared the benefits identified for the runs under each of five Implementation Plan management alternatives.

In the Alternatives Analysis, we found only small differences between alternatives in the benefits metrics. The key exception was Alternative 6 where benefits were consistently greater than for the other alternatives. Alternative 6 has the largest notch, highest max design flows (12,000 cfs), provides the most suitable habitat, and entrains the most fish of the modeled alternatives. Alternative 6 provides access to the Yolo Bypass at lower flows than under existing conditions and, presumably, introduces variability in the accessibility of suitable rearing habitat for fish that, in turn, increases fork length variation and arrival timing variation at Chipps Island.

In the Effects Analysis, we found an interactive effect of the rearing rule and rearing survival value. We suggest that both should be targets for additional investigations, but recognize the challenges in the design of such studies. This includes studies of fall- and spring-run survival through the Yolo Bypass. A better understanding of survival on and carrying capacity of the Yolo Bypass are warranted.

BACKGROUND

Significant modifications have been made to California's Central Valley (CV) floodplains for mining, agriculture, urban development, and (more recently) water supply and flood control purposes. The resulting loss of floodplain rearing habitat, migration corridors, and food web production has significantly impacted native fish species whose life history strategies depend upon seasonally inundated habitat. The Yolo Bypass, which currently experiences at least some flooding in approximately 80% of years, still retains many characteristics of historic floodplain habitat that are favorable to a suite of fish species (CDWR 2012). In approximately 70% of years, the Fremont Weir overtops, joining flows from the Sacramento River with flows entering the Yolo Bypass from western tributaries (CDWR 2012).

Although the primary function of the Yolo Bypass is to provide flood control management for the surrounding metropolitan areas, the Yolo Bypass is also managed as mixed-use, providing land for both private agriculture and public recreation. In recent years, the Yolo Bypass has also been recognized as important rearing, spawning, and migratory habitat for numerous native fish species (CDWR 2012), accessed perennially through a narrow channel that spans the eastern edge of the Yolo Bypass. Studies in the region document favorable outcomes for ecosystem functions and desirable species assemblages

42   as a result of targeted management action (Kiernan 2012, Jeffres et al. 2008, Sommer et al. 2001b).
43   When combined with the Yolo Bypass's current role in successful, multi-faceted land uses, this suggests
44   that the floodplain can support human demands without eliminating the processes needed to sustain
45   aquatic species (Opperman et al. 2009). Thus, the Bypass is identified by several state and federal
46   entities as a potential site for habitat restoration, with the goal of benefitting threatened and endangered
47   fish species.

48   As part of the effort to evaluate the site for restoration, the Yolo Bypass Salmonid Habitat Restoration
49   and Fish Passage Draft Implementation Plan (Implementation Plan) was prepared jointly by the
50   California Department of Water Resources (DWR) and the U.S. Bureau of Reclamation (Reclamation)
51   to address two specific Reasonable and Prudent Alternative (RPA) Actions set forth in the NMFS
52   Operation Biological Opinion:

53   • RPA Action I.6.1: Restoration of floodplain rearing habitat, through the increase of seasonal
54   inundation within the lower Sacramento River basin; and

55   • RPA Action I.7: Reduce migratory delays and loss of salmon, steelhead, and sturgeon, through
56   the modification of Fremont Weir and other structures of the Yolo Bypass.

57   Prior to execution of the Implementation Plan, the potential benefits of restoration actions (via the
58   Implementation Plan) on all four CV Chinook salmon runs will be evaluated quantitatively through a
59   targeted modeling effort. The goals of this modeling effort are as follows:

60   • Create a mechanistic, simulation model to quantify and visualize the potential benefits of Yolo
61   Bypass restoration actions on CV Chinook salmon runs that spawn upstream of the Yolo Bypass.

62   • Using the simulation model, quantify lifestage-specific and cumulative impacts of restoration
63   actions on each Chinook salmon run.
64
65   • Conduct a comparison of the benefits identified for Chinook salmon runs under each
66   Implementation Plan management alternative.

Study Species

68   In the CV, Chinook salmon evolved a range of diverse life history strategies (Williams 2006). This
69   "portfolio effect" allowed them to combat the risk posed by highly variable environmental conditions
70   (Carlson and Satterthwaite 2011). Four distinct populations ("runs") of Central Valley Chinook are named
71   for the timing of adult spawning migrations (fall, late-fall, winter, and spring), and are genetically
72   distinguishable. Each run reflects genetically-based adaptations to seasonal conditions in the local
73   environment. Through investment in this diverse portfolio, the species, as a whole, has enormous capacity
74   for resilience and adaptation to local conditions (Carlson and Satterthwaite 2011; Hilborn 2003).
75
76   Apart from those runs that remain in freshwater and migrate the following year (as yearlings), most young
77   CV salmon migrate to the ocean during the first few months following emergence. Juveniles may rear in
78   floodplains, mainstem rivers, and/or estuaries for varying lengths of time before entering the ocean at an
79   appropriate size for survival (between 80-170 mm FL, depending on the run). Chinook salmon spend 1-5
80   years in the ocean before returning to the river as spawning adults, with a small portion of males
81   (precocious) that may never leave freshwater (Foote et al. 1991). These runs and the large populations they
82   once supported (at least 1 to 2 million adults annually; Yoshiyama et al. 1998, 2000) reflect the diverse and
83   productive habitats that historically existed within the region. Over the past 180 years anthropogenic

84 effects—including mining, flood protection, power generation, water development, stream and floodplain
85 conversion, water quality degradation, invasive species, harvest, and hatchery management—have stressed,
86 altered, and depleted these resources (Yoshiyama et al. 1998, 2000; Williams 2006; Israel et al. 2011).
87 Global parameters, such as ocean conditions, have also demonstrated a marked effect on adult escapement
88 (Lindley et al. 2007, 2009). In the past 3 decades, the CV spring and winter runs were listed under the
89 United States Endangered Species Act (ESA) of 1973. Habitat modification on nearly all major CV rivers
90 has resulted in selective loss of habitats, which disproportionately affect certain life history components of
91 each run (Carlson and Satterthwaite 2011; McClure et al. 2008; Lindley et al. 2007).

Study System

93 The Yolo Bypass Salmon Benefits Model (hereafter SBM) is comprised of the following key locations and
94 systems (Figure 1).
95
96 **Sacramento River**: The mainstem Sacramento River is the primary migratory route for model fish through
97 the system. In the SBM, the only place where fish can choose another route is at Fremont Weir.
98
99 **Knights Landing**: The location of a rotary screw trap on the Sacramento River and the point where fish
100 enter the model.
101
102 **Fremont Weir**: A passive weir, located about 11 km downstream of Knights Landing, that serves as the
103 primary location for flow to enter the Yolo Bypass from the Sacramento River during periods of high flows.
104 The alternative management scenarios involve designing a notch in the Fremont Weir to increase flow
105 management capabilities (see Modeled Alternatives). Model fish are only able to enter the Yolo Bypass via
106 the Fremont Weir.
107
108 **Verona**: Location in Sacramento River, about 3 km downstream of Fremont Weir, where Sacramento River
109 flow is modeled. Because the hydrodynamic properties of the system are complex at Fremont Weir,
110 Sacramento River flow immediately above Fremont Weir is estimated partly based on the flow in the
111 Sacramento River at Verona (see Entrainment).
112

Figure 1. The spatial extent of the Salmon Benefits Model, which tracks Chinook salmon life history from emigrating juveniles to adult escapement, beginning in the mainstem Sacramento River just upstream of Fremont Weir at the location of the Knights Landing screw trap. Circles identify key locations relevant to model functions; stars represent cities.

Feather River: Flow from the Feather River enters the Sacramento River just upstream of Verona and is used in the estimation of flow into the Yolo Bypass at Fremont Weir (see Entrainment).

Canal Complex: The primary migratory pathway through the Yolo Bypass comprised of the Tule Canal and the Toe Drain. The Canal Complex is perennially watered and provides a passage route for juvenile salmon. The route through the Canal Complex is approximately 30 km shorter than staying in the Sacramento River.

Yolo Bypass: Throughout this document, Yolo Bypass is generally used inclusively to refer to the Canal Complex and the adjacent floodplain habitat.

Rio Vista: The approximate location of the confluence between the Canal Complex and the Sacramento River. Model fish from the Sacramento River and Yolo Bypass routes come back together at Rio Vista. However, fish move and survive at route-specific rates despite occupying the same reach. All fish grow at the same rate while migrating from Rio Vista to Chipps Island, though.

Modeling Approach

135 The primary goal of the SBM is to compare fish benefits among Fremont Weir notch alternatives (see
136 Modeled Alternatives). The goal of the model is **not** to answer if salmon benefit from a notch in
137 Fremont Weir. The secondary goals of the SBM are to hone our intuition about the modeled system and
138 to identify knowledge and data gaps. The SBM cannot predict all possible trajectories of Chinook
139 salmon populations under the proposed management alternatives. Instead, the SBM provides an
140 experimental system in which the consequences of various sets of assumptions can be rigorously
141 examined and the range of outcomes for modeled alternatives can be compared (Peck 2004).

142 The SBM is a deterministic simulation model. Parameters enter the model as a single value (or series of
143 values) rather being drawn from a distribution of values. We recognize the value of stochastic simulation
144 models. However, the SBM is in an active state of development and working with a deterministic model
145 reduces time in the model development cycle because running the SBM is a computationally intensive
146 process. Although the SBM currently does not include stochasticity, running the model across 15 years
147 provides considerable variation in model behavior. Moreover, the effect of parameters, model rules, and
148 interactions among parameters/rules on model outputs can be evaluated with simulation experiments.
149 We fully expect that future work on the SBM will include the development of a stochastic version of the
150 model.

151 Unlike a life cycle model, where progeny from one brood year are allowed to influence outcomes of the
152 next, the SBM takes a production model approach to simulation, where individual brood year-classes are
153 tracked separately. The model simulates and tracks key stages of Chinook salmon life history, from the
154 point of freshwater emigration (just upstream of the Yolo Bypass entrance) to the number of returning
155 adults (escapement), and quantifies the potential life stage-specific and cumulative impacts of
156 restoration actions on fish size and abundance. As a general modeling approach, simulation has been
157 successfully applied to evaluate the effects of other restoration actions on CV Chinook salmon
158 populations, including the following:

159 • The San Joaquin River Emigrating Salmonid Habitat Estimation (ESHE) model to quantify the
160   rearing and emigration habitat needs of future restored populations of fall-run and spring-run
161   Chinook salmon in the San Joaquin River as part of the San Joaquin River Restoration Program
162   (SJRRP 2012).

163 • The Interactive Object-oriented Simulation (IOS) life cycle model (Zeug et al. 2012) to evaluate
164   the effects of the NMFS alternative scenarios of Central Valley water operations on the life cycle
165   and abundance trends of winter-run Chinook salmon.

166 • The Delta Passage Model (DPM) to evaluate the effects of Bay Delta Conservation Plan (BDCP)
167   water scenarios on the Delta emigration survival of all Central Valley runs of Chinook salmon
168   (BDCP 2013).

169 The SBM begins tracking juvenile Chinook salmon in the mainstem Sacramento River just upstream of
170 Fremont Weir, at the location of the Knights Landing screw trap (Figure 1). The model runs on a daily
171 time-step during the CV Chinook salmon juvenile emigration period, from October 2nd until all modeled
172 fish have died or entered the Pacific Ocean, usually by June 30th of the following year. Although the
173 Chinook salmon life cycle occurs over a 2 to 4-year period, the model only explicitly tracks the daily
174 movement and abundance of Chinook salmon until ocean entry (Figure 2). Once modeled fish enter the
175 ocean, the model instantaneously calculates ocean survival and upstream adult migration survival to
176 estimate the number of returning adults. Importantly, the estimates of the number of returning adults for
177 each brood year-class do not influence the number of juveniles entering the model in subsequent years.

178 Finally, the model quantifies the effects of management alternatives on individual life stages to estimate
179 the number of returning adults produced under each alternative.

180

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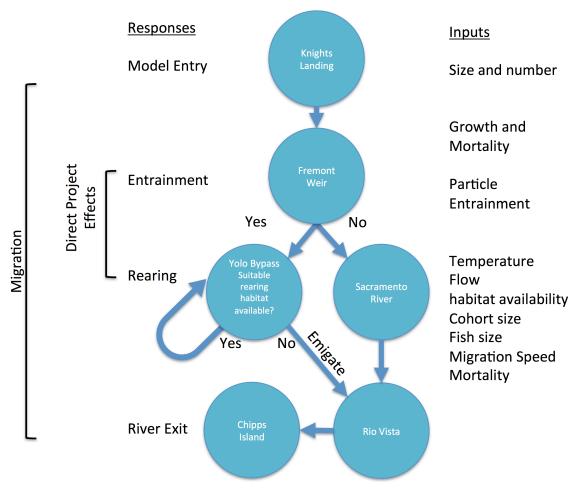
182 **Figure 2.** Conceptual overview of Salmon Benefits Model. The input parameters and relationship that affect
183 model components are shown on the right. The potential responses of model fish are shown on the left. The
184 project effects of the alternative management scenarios directly affect the entrainment and rearing responses of
185 model fish.

Modeled Alternatives

187 The SBM uses the output of the 2D hydrodynamic model TUFLOW (BMT WBM 2013) under existing
188 conditions and five alternatives involving a notch in Fremont Weir (Table 1). The TUFLOW output
189 includes daily raster files (cell size = 50x50') of depth and velocity over a 15-year period (1997-2011)
190 across the entire study area for each alternative. Depth and velocity data were aggregated to a coarser
191 resolution (cell size = 300x300') to reduce computational demands of frequent loading of raster files in
192 the SBM. The TUFLOW output also includes a 15-year time series of flow overtopping Fremont Weir,
193 flow through the notches in the alternatives, Sacramento River flow at Verona, and Feather River flow
194 entering the Sacramento River (just upstream of Verona).

195 **Table 1.** Description of alternatives evaluated with the Salmon Benefits Model. The alternatives differ in the
196 design of a notch in Fremont Weir. Alt02 and Alt03 were not provided for analysis in the Salmon Benefits Model.

Alternative	Description	Alignment	Design Flow (cfs)	Closure Date
Alt01	30' bottom width, 30' bench, no levee	East	6,000	March 15th
Alt04	60' bottom width, 30' bench, no levee, downstream water control structures	West	3,000	March 15th
Alt04b				March 7th
Alt05	Intake A & B: 80' bottom width; Intake C: 130' bottom width; Intake D: 142' bottom width	Central	3,900	March 15th
Alt06	200' bottom width	West	12,000	March 15th
Exg	Flow over existing weir	--	--	--

197

MODEL DOCUMENTATION

Modeling Platform

The SBM was developed in NetLogo, an integrated modeling environment that is a powerful tool for scientific modeling (Lytinen and Railsback 2012). NetLogo is free, open source, and cross platform. The highly readable syntax of the programming language, thorough documentation, and widgets for graphical-user-interface (GUI) elements allow for rapid prototyping of new models in NetLogo.

Model Components

Model Entry

Initial Abundance

To determine the initial juvenile abundances of each Chinook salmon run entering the model, we converted historical spawner abundance estimates from each water year (California Department of Fish and Wildlife GrandTab database) to juvenile emigrants, using Chinook salmon populations that spawn upstream of Fremont Weir in the Sacramento River Basin (Table 2). We achieved this first by converting spawner abundance to number of female spawners, assuming a sex ratio of 0.5. Next, the number of female spawners was converted to number of deposited eggs by multiplying female spawners by run-specific estimates of fecundity (spring-run = 4,900; fall-run = 5,500, late-fall-run = 5,800, winter-run = 3,700; Moyle 2002). Finally, the number of eggs was converted to juveniles by multiplying estimated deposited eggs by 0.25, which is the average egg-fry survival estimate for the Upper Sacramento River (Martin et al. 2001). The resulting numbers of juveniles entering the model for each run are presented in Table 2.

Table 2. Annual run-specific historical estimated escapement values for Chinook salmon populations that spawn upstream of Fremont Weir in the Sacramento River Basin and resulting number of Chinook salmon juveniles of each run entering the Salmon Benefits Model under each water year.

Water Year	Spring-run		Fall-run		Late-fall-run		Winter-run	
	Escapement	Juveniles	Escapement	Juveniles	Escapement	Juveniles	Escapement	Juveniles
1997	2,658	1,628,025	263,653	181,261,438	1,385	1,004,125	1,012	468,050
1998	1,431	876,488	326,558	224,508,625	5,056	3,665,600	836	386,650
1999	23,677	14,502,163	166,380	114,386,250	42,965	31,149,625	2,992	1,383,800

2000	6,092	3,731,350	329,982	226,862,625	15,758	11,424,550	3,288	1,520,700
2001	5,342	3,271,975	329,996	226,872,250	12,883	9,340,175	1,350	624,375
2002	12,952	7,933,100	446,938	307,269,875	21,813	15,814,425	8,224	3,803,600
2003	12,769	7,821,013	702,409	482,906,188	43,017	31,187,325	7,441	3,441,463
2004	8,583	5,257,088	397,094	273,002,125	11,198	8,118,550	8,218	3,800,825
2005	9,562	5,856,725	240,767	165,527,313	15,282	11,079,450	7,869	3,639,413
2006	14,044	8,601,950	329,442	226,491,375	18,614	13,495,150	15,839	7,325,538
2007	8,013	4,907,963	247,739	170,320,563	16,450	11,926,250	17,290	7,996,625
2008	6,755	4,137,438	77,836	53,512,250	13,442	9,745,450	2,541	1,175,213
2009	4,489	2,749,513	63,350	43,553,125	10,483	7,600,175	2,830	1,308,875
2010	2,492	1,526,350	39,385	27,077,188	10,084	7,310,900	4,537	2,098,363
2011	1,904	1,166,200	128,904	88,621,500	10,039	7,278,275	1,596	738,150

221 ### *Entry Timing and Size*

222 Model entry for Chinook salmon is the location of the Knights Landing (KL) rotary screw trap (RST)
223 operated by the California Department of Fish and Wildlife (CDFW), 11 kilometers upstream of
224 Fremont Weir (River KM 144) on the Sacramento River (Figure 1). Knights Landing RST data were
225 then used to inform the initial entry timing and size of the daily juvenile salmon cohorts entering the
226 model for all 15 water years (1997-2011). Because variation in daily RST catch rates can be highly
227 influenced by variability in capture efficiency, we used catch per unit effort data (CPUE) as summarized
228 by Roberts and Israel (2012). Daily CPUE for each run was divided by the sum of all daily run-specific
229 CPUEs throughout a water year to estimate the daily proportion of each run entering the model each day
230 (Figure 3).

231
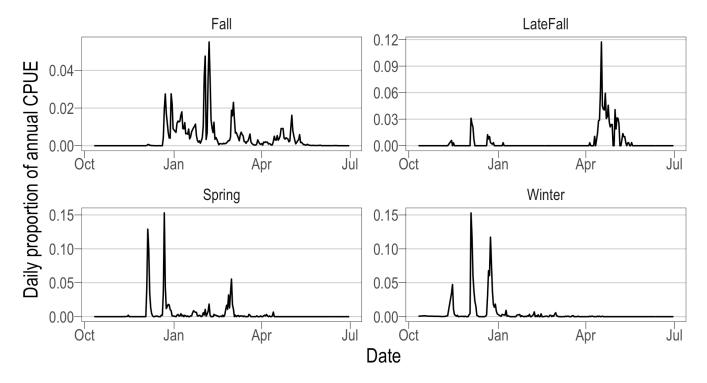
232 **Figure 3.** The daily proportion of juvenile Chinook salmon of each run entering the model during water year
233 2006**.** Note, the y-axes are not all set to the same scale.

234   We used generalized additive models (GAMs) to fit smooth functions of fork length (FL) versus date for
235   each run and water year. The GAMs were used to estimate the fork length of daily cohorts of each run
236   entering the model and allow for predictions on days where fish were caught in the RST but not
237   measured (Figure 4). There is a strong correlation ($r = 0.98$) between the GAM predictions and the mean
238   daily fork length.

239
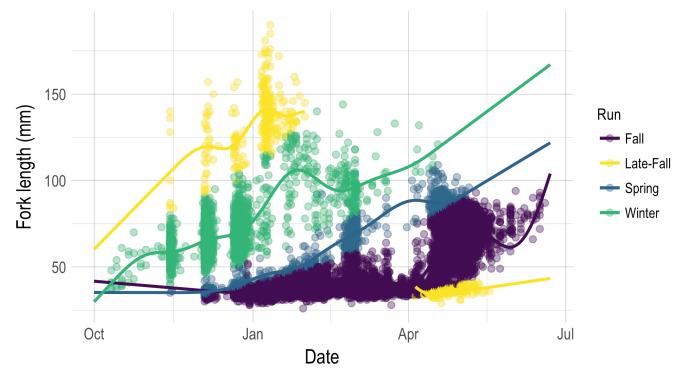
Figure 4. The size of fish captured in the Knights Landing RST (points) and the GAM smooth functions (lines)
241   for water year 2006.

242   Length-at-date criteria were used to assign fish captured at KL RST to each run. Specifically, fish were
243   assigned to a run using the River Model, which was developed by CDFW to classify individual salmon
244   to temporal runs in the upper Sacramento River (Fisher 1992). The logic behind length-at-date criteria is
245   that CV Chinook salmon runs spawn at different times of year, and if the same growth trajectory is
246   assumed, the size of any run is unique on any date, therefore allowing for differentiation of these stocks.

Entrainment

248   The daily proportion of juvenile Chinook salmon of each run entrained onto the Yolo Bypass is
249   estimated by multiplying the daily abundance of juvenile salmon of each run arriving at Fremont Weir
250   by the proportion of Sacramento River flow entering the Bypass. We followed the approach of DWR
251   (2017) and calculated the proportion of flow entering the Yolo Bypass (P_{YB}) through the notch as

$$P_{YB} = Q_{Notch}/(Q_{Notch} + Q_{VON} - Q_{FEA} - Q_{SUT} - Q_{NCC}) \qquad \text{(Eq. 1)}$$

253   where Q_{Notch} is the flow through the proposed notch, Q_{VON} is the Sacramento River discharge at Verona,
254   Q_{FEA} is the Feather River discharge as it enters the Sacramento River (upstream of Verona), Q_{SUT} is the
255   discharge from the Sutter Bypass, and Q_{NCC} is the discharge from the Natomas Cross Canal. When
256   Fremont Weir is overtopping, the proportion of flow entering the Yolo Bypass is calculated as

$$P_{YB} = (Q_{FRE} + Q_{Notch})/(Q_{FRE} + Q_{Notch} + Q_{VON} - Q_{FEA} - Q_{NCC}) \qquad \text{(Eq. 2)}$$

258 where Q_{FRE} is the flow overtopping Fremont Weir. In this equation, the Sutter Bypass discharge is
259 removed from the denominator, which makes the flow proportion based on the combined flow from the
260 Sacramento River and Sutter Bypass (DWR 2017). Daily values of P_{YB} below zero or above one (based
261 on above calculation) are set to zero and one, respectively. Similar to Roberts and Israel (2012), we
262 assume that juvenile Chinook salmon (regardless of size or abundance) are equally distributed across
263 and throughout the water column and enter the Yolo Bypass in proportion to the flow at the Weir.

Migration

265 The survival and movement behavior of SBM model juvenile salmon depends on their migratory route
266 and the Water Year in which the cohort emigrates. Model fish migrating through the Sacramento River
267 do not engage in explicit rearing behavior during their migration. The primary migratory pathway
268 through the Yolo Bypass is the Canal Complex, which remains inundated year-round and provides a
269 passage route for juvenile salmon. Model salmon migrating through the Yolo Bypass will stop their
270 migration and engage in rearing behavior based on the availability of suitable adjacent rearing habitat.
271 After rearing, Yolo Bypass fish move back to the Canal Complex and resume their migration
272 downstream when floodplain habitat recedes or when they experience a migration trigger (see
273 Floodplain Rearing).

274 There is very little data available on the survival and migratory behavior of juvenile Chinook salmon in
275 the Yolo Bypass. Slightly more data is available for the Sacramento River (see Perry et al. 2010, Michel
276 et al. 2015), but comparison is problematic in the absence of Yolo Bypass estimates in the same years
277 and hydrological conditions. For the SBM, we have incorporated empirical data on migration and
278 survival rates for the three years where data from both the Sacramento River and the Yolo Bypass are
279 available, so that assumptions inherent in extrapolating the empirical data to all 15 modeled water years
280 would be consistently applied throughout the model.

281 Migration and survival rates are available for both the Sacramento River and the Yolo Bypass in three
282 years: 2012, 2013, and 2016 (Johnston, *unpublished data*, Perry, *unpublished data*). To apply results
283 from these studies across all 15 water years modeled in the SBM, we calculated the Euclidean distance
284 between the Fremont stage (NAVD88) time series in each data year (2012, 2013, 2016) and each
285 modeled water year (1997-2011). The lowest Euclidean distance across data years indicates the best
286 match for a given water year (Table 3). The estimated migration and survival rate values from the data
287 years (see below) were then applied to each modeled water year according to their best matching data
288 year.

289 **Table 3.** Euclidean distances for comparisons of Fremont stage time series across modeled water years (1997-
290 2011) and data years (2012, 2013, 2016). The smallest value in a row indicates the best match between the
291 modeled water year and the data year.

Water Year	2012	2013	2016
1997	164.72	132.81	154.50
1998	207.48	219.93	190.63
1999	148.09	145.31	141.59
2000	129.82	150.50	112.48
2001	72.70	95.02	94.15
2002	98.26	66.07	110.51
2003	132.42	128.37	136.30

2004	132.75	120.28	121.46
2005	110.53	110.11	121.98
2006	202.89	205.18	183.72
2007	65.15	81.40	109.03
2008	81.71	93.83	103.75
2009	83.82	111.79	116.34
2010	82.82	117.00	96.14
2011	142.12	145.22	144.17

292

Migration Rates

294 Migration rates for emigrating cohorts in each route were calculated from available empirical data from
295 the modeled routes (Table 4). Migration rate data were available for hatchery, late-fall run juvenile
296 Chinook salmon emigrating through the Sacramento River and the Canal Complex in three years: 2012,
297 2013, and 2016 (Johnston, *unpublished data*, Perry, *unpublished data*). Empirical data on movement rate
298 for these years encompass water discharge – that is, the observed movement rates reflect the speed of
299 fish emigrating in the corresponding flow for those three years. Mean movement rates from the three
300 years of empirical data were then applied to the modeled water years according to similarity in the
301 Fremont stage time series for those years.

302 **Table 4.** Mean migration rates (km/day) in the two migratory routes of the SBM, calculated from acoustically-
303 tagged emigrating late-fall run juvenile Chinook salmon.

Year	Sacramento River	Canal Complex
2012	17.4	10.7
2013	11.4	7.5
2016	60.5	21.4

304

Survival

306 In the SBM, overall mortality in the Yolo Bypass includes mortality while migrating through the Canal
307 Complex (gauntlet model) and mortality while rearing on the floodplain (exposure model). All fish that
308 migrate through the Canal Complex experience migrating mortality. However, fish that rear on the
309 floodplain also experience rearing mortality. Estimates of migrating survival are based on acoustic
310 telemetry studies of large, late-fall run juvenile Chinook salmon that are not expected to stop to rear
311 while emigrating through the Yolo Bypass. Values of rearing survival are not based on empirical data,
312 but the effect of the rearing survival value is explored in the Effects Analysis. Additionally, only SBM
313 fish that migrate down the Yolo Bypass have the opportunity to engage in rearing. Thus, all mortality for
314 fish migrating down the Sacramento River originates from migration mortality because no explicit
315 rearing takes place along the Sacramento River route in the SBM.

Migrating Survival

317 In the SBM, cohorts actively migration downstream via either the mainstem Sacramento River, or the
318 Canal Complex in the Yolo Bypass. Survival was estimated with a Bayesian implementation of a
319 Cormack-Jolly-Seber model (adapted from Kery and Schaub 2012) based on empirical survival studies

320 conducted of comparable reaches within the two migratory systems (Johnston, *unpublished data*, Perry,
321 *unpublished data*, Table 5). The survival values were converted to survival per kilometer (S_{km}) as
322 follows:

$$S_{km} = S^{\left(\frac{1}{reach\ length}\right)} \qquad\text{(Eq. 3)}$$

324 **Table 5.** Survival estimates for reaches available from empirical studies of acoustically-tagged late-fall run
325 juvenile Chinook salmon emigrating in 2012, 2013, and 2016.

Year	Migration Route	Reach	Distance (km)	Survival Estimate	Survival Per Kilometer
2012	Sacramento River	Knights Landing – Above Freeport	46.3	0.720	0.9929
2012	Sacramento River	Above Freeport – Chipps Island	106.2	0.615	0.9954
2013	Sacramento River	Knights Landing – Below Freeport	74.1	0.508	0.9909
2013	Sacramento River	Below Freeport – Chipps Island	78.3	0.453	0.9899
2016	Sacramento River	Verona – Freeport	52.8	0.958	0.9992
2016	Sacramento River	Freeport – Chipps Island	80.8	0.737	0.9962
2012	Yolo Bypass	Hwy I-5 – Chipps	90.1	0.470	0.9897
2013	Yolo Bypass	Hwy I-5 – Chipps	90.1	0.180	0.9795
2016	Yolo Bypass	Hwy I-5 – Chipps	90.1	0.551	0.9933

327 The estimates of survival per kilometer (Table 5) from the three years of empirical data were then
328 applied to the modeled water years according to similarity in the Fremont stage time series for those
329 years. Applying migration survival on a per kilometer basis is known as a gauntlet model (Anderson et
330 al. 2005) because migrating fish need to move through a gauntlet of predators to reach the ocean and
331 cannot reduce their predation risk by migrating at a faster rate. Thus, migration rate does not affect
332 migrating survival in the SBM.

Rearing Survival

334 In the SBM, cohorts rearing on the floodplain experience a daily survival of 0.99. A survival model with
335 survival as a function of time is known as an exposure model (Anderson et al. 2005) because the
336 probability of survival is decreased with an increase in time spent rearing and exposure to predators. In
337 the model, fish are trading off increased growth on the floodplain (see

338 Growth) with the additional mortality incurred during rearing (relative to not rearing). [Note, this is not
339 an optimality model; the rearing rules could produce sub-optimal rearing durations depending on the
340 value chosen for rearing survival.] The growth-survival trade-off is reflected in the probability of
341 returning as an adult because ocean survival is modeled as a function of fork length at ocean entry (see
342 Ocean Residence). Floodplain rearing reduces the probability that a juvenile fish reaches the ocean, but
343 the increased size from floodplain rearing increases the probability of surviving during ocean residence.

344   Given the floodplain growth rate and the ocean survival relationship used in the model, and ignoring
345   survival during migration, the minimum daily rearing survival value to make rearing worthwhile (i.e.,
346   growth benefit outweighs rearing mortality) is approximately 0.99 (see
347   https://fishsciences.shinyapps.io/yolo-bypass-rearing-survival/). This rearing survival value is not based
348   on empirical data. However, in the Effects Analysis, we explore the implications of lower rearing
349   survival on the conclusions drawn from the SBM.

Floodplain Rearing

Suitable Habitat

352   We took a simplified approach to movement through the Yolo Bypass. For example, all cohorts move
353   downstream along the eastern edge of the Yolo Bypass in the Canal Complex and movement between
354   the Canal Complex and suitable habitat on the floodplain is instantaneous and incurs no mortality. Also,
355   cohorts have perfect knowledge of the current (but not future) availability of suitable habitat. However,
356   because the Yolo Bypass covers a large geographic extent, we included a spatial constraint and divided
357   the Yolo Bypass into 5 bands that are roughly 14-km long from north to south. Cohorts are only able to
358   access suitable floodplain habitat located within the band that they are currently moving through. The
359   length of the bands (14 km) is longer than the width (~ 3-9 km) of a fully inundated Yolo Bypass. If
360   suitable habitat is available within a band for a given cohort on a given day, the cohort will move onto
361   the available suitable habitat and rear on the floodplain. Habitat suitability criteria for Sacramento River
362   juvenile Chinook salmon (USFWS 2005) were used to define suitable floodplain rearing habitat for fry
363   (<70 mm FL) and smolts (≥70 mm FL; Kjelson et al. 1982). Suitable habitat for fry was characterized as
364   0.39–4 ft deep with velocities less than 1.6 ft/s, and for smolts as 0.39–8 ft deep with velocities less than
365   1.6 ft/s (USFWS 2005).

366   On any given day, the model estimates the daily habitat area requirements of the cohort to determine
367   whether enough suitable floodplain rearing habitat is available to support all or a part of the cohort. The
368   territory size required by each fish is estimated with a linear model on a log-log scale as a function of
369   fish fork length based on data collected for salmonids (Grant and Kramer 1990; Figure 5)

$$\tau = 10^{-5.44 + 2.61 * \log_{10} L} \tag{Eq. 4}$$

371   where τ is territory size (m^2) and L is fork length (mm). The amount of suitable habitat claimed by a
372   given cohort is the sum of the territory sizes of all individuals in the cohort. Suitable habitat is occupied
373   in 900-ft^2 patches by the first cohort that reaches the unoccupied habitat. If there is enough suitable
374   habitat for the full cohort, then the cohort claims the number of habitat patches that it needs. If there is
375   only enough suitable habitat for part of the cohort, then the cohort is split, with part of the cohort
376   claiming the available patches, and the other cohort part continuing to migrate downstream in the Canal
377   Complex. Each day the amount of suitable habitat is updated and the above process is repeated.

378
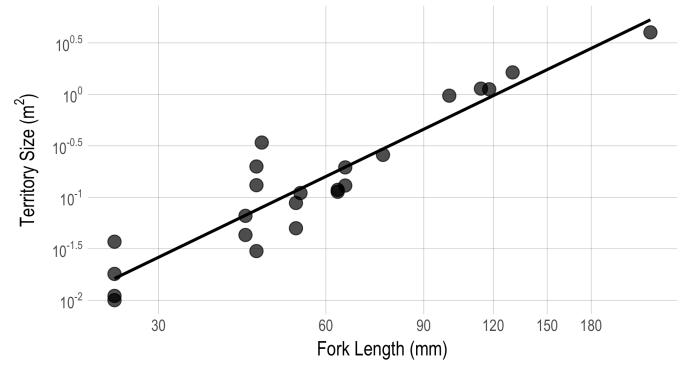
Figure 5. Territory size versus fork length relationship for salmonids based on data from Grant and Kramer
(1990). Circles are observations and line is fitted relationship used in the Salmon Benefits Model.

Rearing Rules

Although some precocious males never leave freshwater, we assume the value/numbers of these fish are
negligible. Therefore, in the model, Chinook salmon do not rear in freshwater indefinitely, and we
incorporated rearing rules that constrain the time that a cohort spends rearing on the floodplain. The
model uses these rearing rules to decide whether a cohort migrating through the Canal Complex
continues to migrate or whether it will rear in adjacent suitable habitat. The rearing rules are simple
heuristics based on temperature, fish size, and time of year.

The water temperature rule is based on daily water temperature data collected by the California
Department of Water Resources (DWR) Aquatic Ecology Section RST site located in the Toe Drain
near the north-east tip of Little Holland Tract for years 1998-2011. Because both growth rates and
smoltification (ATPase activity) of juvenile Chinook salmon have been shown to decrease at water
temperatures above 20°C (Marine 1997; Marine and Cech 2004), the first day that average water
temperatures exceeded 20°C was set as a maximum date that fish would rear on the floodplain. The Toe
Drain water temperature data indicated that June was the first month that average daily water
temperatures consistently exceeded the 20°C threshold across nearly every year. Thus, June 1st was set
as the date when rearing fish would stop rearing and continue migrating through the Canal Complex.

Under the assumption that there is a theoretical maximum size when fish smoltification and resulting
directed movement toward the ocean will occur, the largest Chinook salmon juvenile observed to be
entering the ocean in recent years was used to determine a threshold size used to move fish off of the
floodplain and back to the Canal Complex to resume downstream migration. The threshold fish size was
based on the maximum size of Chinook salmon historically observed to emigrate out of the Central
Valley. The maximum fork length of un-marked Chinook salmon observed migrating past Chipps Island
in 2010 and 2011 was 120 mm (Speegle et al. 2013). Therefore, modeled fish move back to the Canal
Complex and resume downstream migration once reaching a fork length of 120 mm.

405 One of the main seasonal triggers of smoltification and resulting downstream migration for salmonids is
406 changes in photoperiod as the season progresses (Thorpe 1988). Because photoperiod is tied to time-of-
407 year, a second migration trigger was applied (run timing trigger) that was based on the last dates that
408 each run was observed passing Chipps Island during years 2007-2011 (USFWS 2010; USFWS 2012;
409 Speegle et al. 2013). The last observed dates at Chipps Island were May 15 for winter-run, May 31 for
410 spring-run, July 31 for fall-run, and February 15 for late-fall-run. For each cohort, the model back-
411 calculates the date to stop rearing based on the distance to Chipps Island, migration rate, and run-timing
412 trigger date.

Growth

414 In the SBM, growth is calculated as

$$L_t = g^t L_0 \qquad \text{(Eq. 5)}$$

416 where L_t is fork length at time t, L_0 is fork length at time 0, and g is the daily proportional growth rate.
417 The key assumption of this model is that fish of all sizes grow by the same proportion in a day, but
418 larger fish will increase their size by a greater absolute amount. For example, if g is 1.01, a 30-mm fish
419 will grow 0.3 mm in one day, but a 100-mm fish will grow 1.0 mm in one day.

420 The proportional growth rate can be estimated from empirical studies of fish growth (e.g., Jeffres et al.
421 2008) by re-arranging the growth equation as follows

$$g = \left(\frac{L_t}{L_0}\right)^{1/t} \qquad \text{(Eq. 6)}$$

423 We used this equation to estimate growth rates from empirical studies of juvenile Chinook salmon in
424 California's Central Valley (Table 6). In the model, we set daily growth rates at 1.005, 1.006, and 1.012
425 for the Sacramento River, Canal Complex, and Yolo Bypass floodplain, respectively. We arrived at
426 these values by averaging the values from Table 6. When a study included multiple replicates or
427 treatments within a year, we first averaged across those replicates/treatments and then averaged across
428 all studies and years.

429 **Table 6.** Growth rates from empirical studies of juvenile Chinook salmon in California's Central Valley.

Location	Year	Initial Fork Length (mm)	Final Fork Length (mm)	Days	Daily Growth Rate	Notes	Source
Sacramento River	2016	54.8	58.2	21	1.003	--	Jeffres 2016[2]
Toe Drain	2016	54.8	62.0	21	1.006	--	
Yolo Bypass floodplain (Knaggs Ranch)	2016	54.8	76.7	21	1.016	--	
	2014	61.0	81.0	15	1.019	PIT tag study; enclosure 1	Katz et al. 2014
		60.6	81.7	15	1.020	PIT tag study; enclosure 2	
		61.9	81.0	15	1.018	PIT tag study; enclosure 3	
		43.0	77.8	35	1.017	Volitional outmigrant study; hatchery origin	

Location	Year	Initial Fork Length (mm)	Final Fork Length (mm)	Days	Daily Growth Rate	Notes	Source
		33.9	53.5	25	1.018	Volitional outmigrant study; wild origin	
	2013	53.6	92.1	39	1.014	Free-swimming; disc field	Katz et al. 2013
		53.6	90.3	39	1.013	Free-swimming; stubble field	
		53.6	88.4	39	1.013	Free-swimming; fallow field	
		52.2	63.9	16	1.013	Penned; hatchery origin	
		52.4	65.9	16	1.014	Penned; wild origin	
	2012	48.0	75.5	42	1.011	Free-swimming	Katz 2012
		48.0	78.0	42	1.012	Penned	
Cosumnes River floodplain	2004	54.9	71.4	32	1.008	FP Veg	Jeffres et al. 2008
		54.9	72.2	32	1.009	Upper pond	
		54.9	66.2	32	1.006	Lower pond	
	2005	54.0	86.6	56	1.008	FP Veg	
		54.1	79.7	56	1.007	Upper pond	
		54.0	74.6	56	1.006	Lower pond	
Yolo Bypass floodplain	1998	57.5	93.7	46.2	1.011	--	Sommer et al. 2001
	1999	56.8	89.0	58.2	1.008	--	
Sacramento River	1998	57.5	85.7	55.4	1.007	--	
	1999	56.8	82.1	58.6	1.006	--	

430

Ocean Residence

432 In the SBM, survival from ocean entry to return at age 3 is modeled as a function of fork length at ocean
433 entry because fish size is positively correlated with ocean survival in salmonids (Ward et al. 1989,
434 McGurk 1996). We were provided a dataset (Will Satterthwaite, *personal communication*) of juvenile
435 Chinook salmon releases and recoveries that were the basis of Satterthwaite et al. (2014). The dataset
436 contains release weight, but not fork length. Thus, the first step was to convert weights to fork lengths.
437 We used catch of fall-run Chinook salmon at the Knights Landing RST from 2000-2012 (Figure 6) to
438 develop the following relationship.

439
$$L = 48W^{0.3}$$
(Eq. 7)

440 where W is wet weight (g) and L is fork length (mm).

441
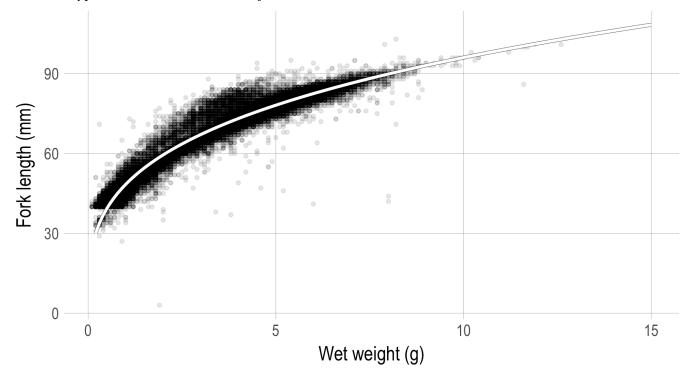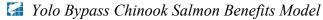
Figure 6. Fork length and wet weight of fall-run Chinook salmon caught at the Knights Landing Rotary Screw Trap from 2000-2012. Circles are observed values and white line is fitted relationship.

Satterthwaite et al. (2014) focused on how release timing in the San Francisco Bay affected ocean survival of fall-run Chinook salmon. They made several decisions about how to filter the dataset to better address their focus on release timing. For our analysis, we excluded fewer records because we wanted a larger size range for fitting a relationship between size at ocean entry and ocean survival. Similar to Satterthwaite et al. (2014), only age-3 recoveries were considered when estimating ocean survival because prior to being caught at age 3, the predominant source of mortality is from natural causes, and recoveries of age 2 and age 4 fish are comparatively rare. We also excluded data from releases in 2006 and 2007 because the fishery was closed in 2008 and 2009, which precluded age-3 recoveries. We fitted a generalized linear model with a quasi-binomial error distribution and a logit link to predict survival, *S*, at age 3 from fish fork length, *L*, at release (Figure 7):

$$S = \text{logit}^{-1}(-7.385 + 0.025L) \tag{Eq. 8}$$
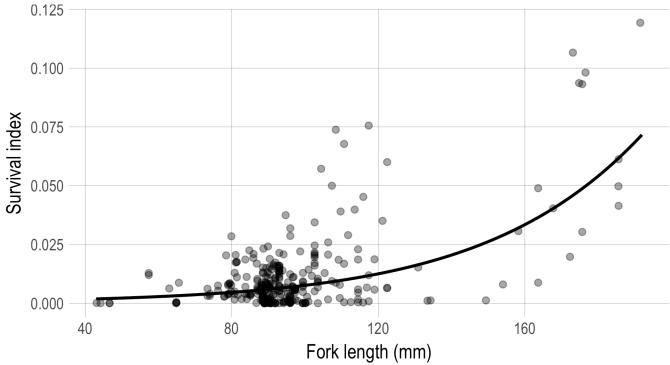
Figure 7. Age 3 survival index versus fish fork length at release for hatchery fall-run juvenile Chinook salmon released in the San Francisco Bay, 1978-2011. Circles are observed values and line is fitted relationship, which is used in the Salmon Benefits Model.

Upstream Migration

Following ocean residence, upstream migration of returning adults from the Bay to Fremont Weir on the Sacramento River was modeled. As a simplifying assumption, the SBM does not include any mortality during the upstream migration of adult returners. In the SBM, we only track the run and number, not size, of returning adults. Thus, upstream migration mortality would not impact comparison of alternatives within a run.

Model Assumptions and Limitations

Due to limited data available for several CV Chinook salmon life stages, traditional statistical estimation models become difficult to apply when attempting to predict outcomes of future management actions (Williams 2006). Unlike predictive models, simulation models can be useful for organizing existing knowledge and identifying gaps in understanding, even if the model predictions are imprecise (Williams 2006). Simulation models should be thought of as experimental systems or aids that are distinct from the "real world" in which the consequences of various sets of assumptions can be examined (Peck 2004). However, model usefulness is measured by how well it captures the interactions of the most important factors and leaves out unimportant ones (Ford 1999), thereby limiting model complexity and simplifying interpretation of results. More complex models can be too dataset-specific and have poor predictive ability, mainly due to estimation error, while simpler models can be too general and incorporate error due to system oversimplification (Astrup et al. 2008). Therefore, we attempted to model the benefits of Yolo Bypass restoration actions on Chinook salmon with a level of complexity that captures the most recent key factors thought to influence fish survival and size, while limiting the inclusion of factors that have low utility for evaluating project effects, or that are unsupported by existing scientific knowledge.

Data Availability

Simulation models depend upon available data to inform model relationships, resulting in a complexity level that matches the depth of knowledge known about a subject (Astrup et al. 2008). When local data is limited, model relationships can often be informed by populations outside the study region, laboratory studies in controlled experimental settings, or artificially raised (hatchery) surrogates. For example, many of our model relationships rely on data from tagged hatchery surrogates. This is because most experimental studies are of hatchery-origin fish, conducted under the assumption that outcomes and behavior are at least similar between fish of different natal origins and animal husbandry. In addition to limited data on naturally-produced fish, many of our relationships are informed by data from a single Chinook salmon run (i.e., fall-run), thereby assuming that all runs move, grow, and survive according to the same rules.

Habitat Suitability

For juvenile salmon to successfully rear, numerous physical requirements must be met including suitable cover (McMahon and Hartman 1989), food availability and water quality (Marine and Cech 2004). Furthermore, flood duration of seasonally inundated habitats can dictate the strength of biotic response to the flood (King et al. 2003). Unfortunately, spatial modeling of water temperature, cover, and biotic production were not available to inform the complex response between Bypass inundation duration and juvenile growth. However, a key assumption of salmonid rearing habitat modeling is that depth and velocity are major predictors of habitat suitability (Raleigh et al. 1986; Keeley and Slaney 1996). Therefore, we simplified our approach and defined suitable habitat based on water depths and velocities alone and modeled juvenile salmon to exhibit an average, consistent growth rate while rearing on the floodplain. We currently assume depth and velocity suitability criteria developed in the adjacent habitat of the Sacramento River (USFWS 2005) is transferable to Yolo floodplain. However, if more information becomes available to inform a more sophisticated relationship between floodplain habitat and juvenile salmon rearing success, model functionality can be changed.

Water Temperature

Water temperature can affect juvenile Chinook salmon survival and health (Marine and Cech 2004), and migratory behavior has been associated with long-term accumulated response to water temperatures, with smoltification rates increasing with increased accumulated thermal units unless the upper threshold is met (ATU; Sykes and Shrimpton 2010; Marine and Cech 2004). However, apart from the water temperature movement trigger, these temperature effects are excluded from the model due to lack of modeled temperature data. The water temperature movement trigger assumes that historical Yolo Bypass water temperatures will likely relate to future water temperatures under the different management alternatives, at least in a very coarse way. If water temperatures are modeled for Yolo Bypass management alternatives in the future, new model functionality could be incorporated to evaluate how different temperature regimes under each alternative affect model outcomes.

Yolo Bypass Entrainment

Models for how juvenile Chinook salmon are distributed in the channel and throughout the water column at the Fremont Weir junction are currently unavailable. Therefore, we assumed that juvenile Chinook salmon are equally distributed across the channel and throughout the water column and enter the Yolo Bypass in proportion to the flow entering the bypass. Similar dispersion assumptions have been used to estimate juvenile salmon entrainment (Kimmerer and Nobriga 2008). However, if more information becomes available to inform a more sophisticated relationship between flow and juvenile salmon entrainment, or if different entrainment alternatives are examined in the future, model functionality can be changed to evaluate alternative mechanisms of entrainment.

Movement

Juvenile salmon movement in the riverine and floodplain portions of the model is greatly simplified and limited by data availability. Modeled fish in the Sacramento River and Canal Complex move one-dimensionally and at an average rate. Migratory behavior in juvenile salmonids is a complex process related to growth, hormonal development, and environmental parameters, all of which may influence habitat use and movement throughout the emigration period (Iwata 1995). While juveniles may shift between rearing and actively migrating during the emigration process (Hoar 1953; Iwata 1995), the mechanisms that inform these complex movements are not well understood or easily modeled. Therefore, we instead modeled the average downstream movement of juvenile Chinook based on simple movement rules. A simplified model was then applied for juveniles rearing on the floodplain. Data is not available to inform model rules for how fish should move across the floodplain in two dimensions, nor is data available to inform simulation of high-resolution territorial behavior on floodplains. Therefore, the model allows fish to immediately colonize proximate habitat, without explicitly modeling individual movement. We assume that all juvenile Chinook set up a territory in the most immediately available and suitable habitat, without prioritization for juveniles of different sizes or runs.

Growth

We assumed that growth rate depends only on fork length and approximate location (i.e., Sacramento River, Canal Complex, floodplain). It is unlikely that growth is homogenous throughout each of these locations, but we assume that our estimates of growth rate reflect average behavior across these locations.

Survival

River

We assumed that juvenile Chinook salmon survive according to a gauntlet model of survival. Survival might be better represented by a survival model that incorporates both distance and time traveled (i.e., XT model; Anderson et al. 2005), but mechanisms underlying the XT model are not yet well understood. We also assumed that mortality was evenly applied from Fremont Weir to Chipps Island along both the Sacramento River and Canal Complex routes. On the Sacramento River route, this is simply an implementation detail because where fish die along that route is not important for the metrics used to evaluate alternatives. On the Canal Complex route, where fish die along the route may have implications for accessing suitable rearing habitat, particularly if most of the mortality occurs from Rio Vista to Chipps Island when no longer have access to floodplain. We assumed that survival estimates from studies of large, hatchery, late-fall run Chinook salmon conducted in 2012, 2013, and 2016 apply to wild fish of other runs and sizes in water years 1997-2011. We also assumed that migrating survival is constant throughout the migration season.

Floodplain

We assumed that floodplain survival operates under an exposure model where time spent rearing reduces the overall survival. Other factors that may influence floodplain survival include the behavior (e.g., habitat selection, activity level) and physical attributes of the fish (e.g., size). We also assumed that floodplain survival is the same throughout the migration season, across Chinook salmon runs and years, and over the whole floodplain. The floodplain survival component of the model can be updated as more data becomes available.

Ocean

568 Studies have shown that juvenile Chinook salmon survival in the ocean can vary due to many factors
569 including entry timing, physical ocean conditions, trophic dynamics, and size or condition of fish upon
570 entry (Satterwaite et al. 2014). However, because we wanted to incorporate a growth-survival trade-off
571 for floodplain rearing in the model, we only incorporated the effect of fish size on ocean survival. The
572 constraint of hatchery release data is that release size is often confounded with release timing. Thus, we
573 may be overestimating the benefit of large size on ocean survival. We are also assuming that the ocean
574 survival relationship, which is based on data from hatchery fall-run Chinook salmon, applies to wild
575 origin fish of all runs.

ALTERNATIVES ANALYSIS

577 In this section, we present the results of an analysis of alternatives involving different designs for a
578 notch in Fremont Weir (see Modeled Alternatives). The analysis of the SBM focused on five metrics to
579 assess the relative benefits of the management alternatives: (1) juvenile survival from Knights Landing
580 to Chipps Island, (2) mean fork length of fish at Chipps Island, (3) coefficient of variation of fork length
581 of fish at Chipps Island, (4), coefficient of variation of arrival timing at Chipps Island, and (5) number of
582 returning adults.

583 The benefits metrics consider the population as a whole rather than by route (i.e., Sacramento River and
584 Yolo Bypass). The proportion of the population entrained onto the Yolo Bypass is relatively small and
585 highly variable. Across all years, runs, and alternatives, the average proportion entrained is 13% (range:
586 0-61%). Thus, big effects on the Yolo Bypass route can be misleading if not placed in context of the
587 whole population.

588 The benefits metrics are calculated on a yearly time scale. Within-year results are available for
589 additional analysis, but are not presented here. The benefits metrics figures are presented on a relative
590 scale to highlight differences between alternatives.

591
$$relative\ change = \frac{alternative - existing}{existing}$$
(Eq. 9)

592 Percentage change can be calculated by multiplying relative change by 100. The difference between
593 each alternative and existing conditions is calculated on an annual basis because of large inter-annual
594 variation in the benefits metrics. The values used to calculate the relative change in benefits metrics are
595 included as tables in Appendix A.

Juvenile Survival to Estuary Entry

597 Juvenile survival is calculated as the total number of juvenile Chinook salmon that arrive at Chipps
598 Island divided by the total number that entered the model at Knights Landing for each water year.
599 Juvenile survival is lower under alternatives than existing conditions (Figure 8; Table A-1).

600 Juvenile fish migrating from Fremont Weir to Chipps Island on the Yolo Bypass route have lower
601 survival in all years than fish migrating through the Sacramento River. Fish that rear on the floodplain
602 during their migration through the Yolo Bypass incur additional mortality while rearing. Relative to
603 existing conditions, the alternatives increase entrainment and generally increase time spent rearing on
604 the floodplain. Late-fall fish experience the lowest relative change (least negative) in juvenile survival
605 because they enter the model at a larger size and exhibit very little rearing behavior.

606
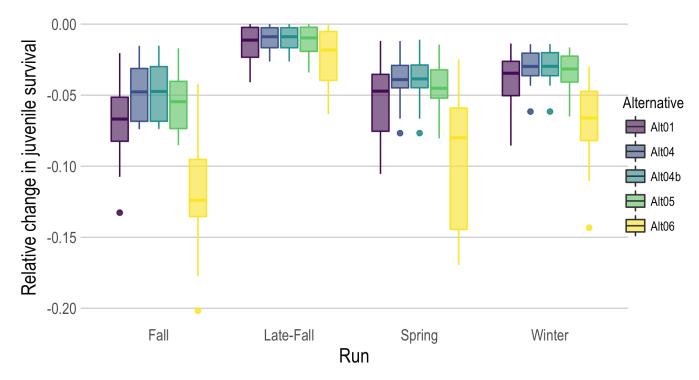
Figure 8. Relative change in juvenile survival from Knights Landing to Chipps Island for 15 years under five alternatives for notches in Fremont Weir. The line near the center of the box is the median, the bottom and top of the box are the 25th and 75th percentiles, respectively, the whiskers show the min/max (unless there are outliers), and the points are outliers (+/- 1.5x interquartile from 75th and 25th percentile, respectively). Note, the y-axis has been truncated to exclude some outliers. See Table A-1 for full set of values.

Juvenile Fork Length at Estuary Entry

Fork length is calculated as the mean fork length of all juvenile Chinook cohorts that arrive at Chipps Island weighted by the abundance of fish in the cohort. Fish grow faster on the floodplain than in the Sacramento River and, thus, mean fork length at Chipps Island is generally higher under the alternatives than under existing conditions (Figure 9; Table A-2.). Late-fall fish are the exception because they enter the model at a larger average size, often above the rearing size threshold (120 mm), and do not benefit from the increased floodplain rearing opportunities provided by the alternatives.

Figure 9. Relative change in mean fork length at Chipps Island for 15 years under five alternatives for notches in Fremont Weir. The line near the center of the box is the median, the bottom and top of the box are the 25th and 75th percentiles, respectively, the whiskers show the min/max (unless there are outliers), and the points are outliers (+/- 1.5x interquartile from 75th and 25th percentile, respectively).

Juvenile Fork Length Variation at Estuary Entry

Fork length variation is calculated as the coefficient of variation in fork length of all cohorts that arrive at Chipps Island weighted by the abundance of fish in the cohort. Using fork length variation as a fish benefits metric reflects the importance of trait variation in ecological dynamics, including those assumed for CV Chinook salmon (Goertler et al. 2016; Bolnick et al. 2011). Fork length variation is higher under alternatives than under existing condition (Figure 10; Table A-3). The alternatives provide access to the Yolo Bypass at lower flows than under existing conditions and, presumably, introduce variability in the accessibility of suitable rearing habitat for fish that, in turn, increases fork length variation at Chipps Island.
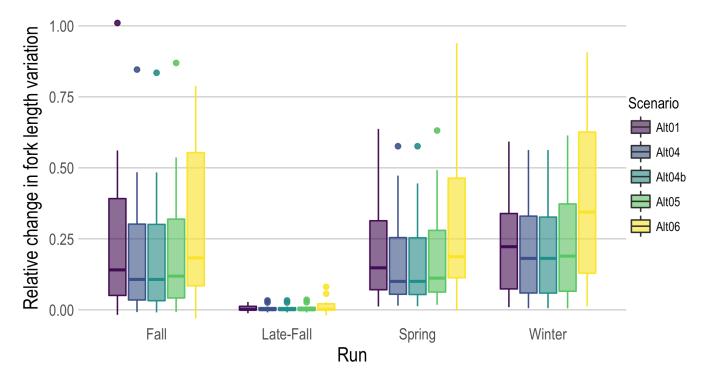
Figure 10. Relative change in coefficient of variation in fork length at Chipps Island for 15 years under five alternatives for notches in Fremont Weir. The line near the center of the box is the median, the bottom and top of the box are the 25th and 75th percentiles, respectively, the whiskers show the min/max (unless there are outliers), and the points are outliers (+/- 1.5x interquartile from 75th and 25th percentile, respectively). Note, the y-axis has been truncated to exclude some outliers. See Table A-3 for full set of values.

Juvenile Timing Variation at Estuary Entry

Entry timing variation is calculated as the coefficient of variation in timing of all cohorts that arrive at Chipps Island weighted by the abundance of fish in the cohort. Timing is measured as day of water year when a cohort arrives at Chipps Island where October 1st is day one. Ocean conditions vary within the migration season (citation) and variation in estuary entry timing may make the population more resilient to changing ocean conditions. Entry timing variation is higher under alternatives than under existing condition (Figure 11; Table A-4). The alternatives provide access to the Yolo Bypass at lower flows than under existing conditions and, presumably, introduce variability in the accessibility of suitable rearing habitat for fish that, in turn, increases estuary entry timing variation.
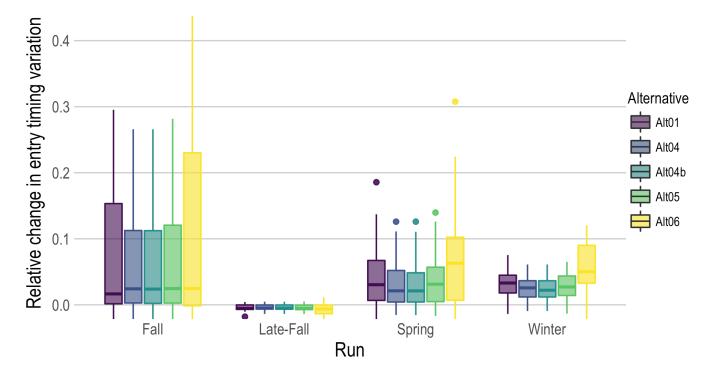
Figure 11. Relative change in coefficient of variation in estuary (Chipps Island) entry timing for 15 years under five alternatives for notches in Fremont Weir. The line near the center of the box is the median, the bottom and top of the box are the 25th and 75th percentiles, respectively, the whiskers show the min/max (unless there are outliers), and the points are outliers (+/- 1.5x interquartile from 75th and 25th percentile, respectively). Note, the y-axis has been truncated to exclude some outliers. See Table A-4 for full set of values.

Returning Adults

The number of returning adult salmon depends on both the number and size of juveniles that arrive at Chipps Island because the ocean survival relationship is a function of size. The returning adults metric shows the combined effect of the juvenile survival and fork length metrics. In other words, the number of returning adults captures the trade-off between floodplain growth and rearing survival. Under most alternatives and years, the alternatives produce more returning adults than existing conditions (Figure 12; Table A-5). Late-fall fish are the exception because they incur the juvenile survival costs of migrating through the Yolo Bypass (Figure 8), but do not reap the growth benefits (Figure 9) provided by access to the floodplain because they enter the model at a larger average size, often above the rearing size threshold (120 mm).
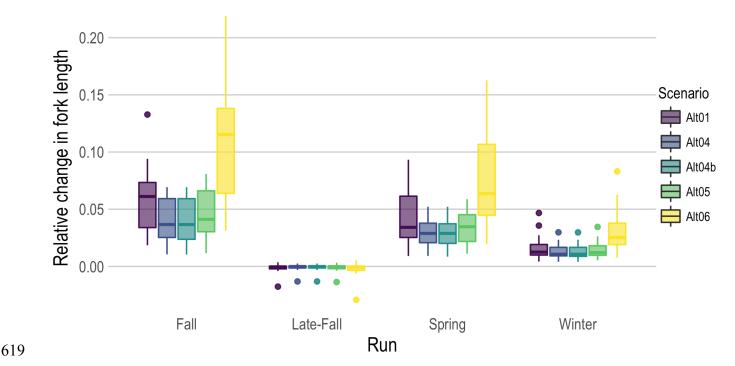
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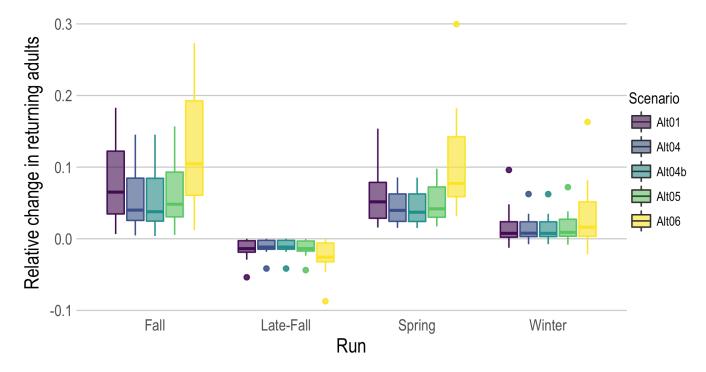
Figure 12. Relative change in number of returning adults for 15 years under five alternatives for notches in Fremont Weir. The line near the center of the box is the median, the bottom and top of the box are the 25th and 75th percentiles, respectively, the whiskers show the min/max (unless there are outliers), and the points are outliers (+/- 1.5x interquartile from 75th and 25th percentile, respectively). Note, the y-axis has been truncated to exclude some outliers. See Table A-5 for full set of values.

Conclusions

In drawing conclusions for the Alternatives Analysis, we focus on three of our fish benefits metrics: returning adults, estuary entry timing variation, and fork length variation. The number of returning adults measures the productivity of the population and incorporates the combined effects of juvenile growth and survival. Moreover, the returning adults metric includes benefits for larger fish in a couple of model components (i.e., growth, ocean survival). In contrast, estuary entry timing variation and fork length variation provide alternative benefits metrics that reflect the value of variation in traits and environmental conditions. Although fish size at ocean entry is a significant predictor of ocean survival, the relationship is noisy (Figure 7) and confounded with estuary entry timing. It's possible that smaller fish may be favored under some ocean conditions, which may increase population stability across years.

For all three focal metrics, Alt06 generated the biggest relative changes. Alt06 has the largest notch and highest max design flows (12,000 cfs) of the modeled alternatives. There is very little difference in the focal metrics among the other alternatives, but Alt01 yields noticeably different relative changes for some runs in some years. Alt01 has the second largest design flow (6,000 cfs) of the notches considered.

The relative change in fork length variation is correlated to relative change in entry timing variation for all runs, except late-fall, with correlation coefficients ranging from 0.72-0.91 across alternatives and runs.

The largest relative changes in returning adults and fork length variation generally do not occur in the same years. For example, for fall- and spring-run in 1999, Alt06 produced a much larger relative change

689 in adult returners than the other alternatives, but there was very little difference among alternatives in
690 fork length variation.

EFFECTS ANALYSIS

692 The SBM includes numerous modeling decisions derived from best available data, expert opinion, and
693 modeling experience. The conclusions drawn from the model results depend on the details of model
694 implementation and it is an important step in the model development process to explore the implications
695 of changing model rules and input parameters on the model results. If changing a model rule produces
696 little or no change in the results, then it suggests that model component is not particularly important and
697 could be simplified or removed from the model. Conversely, if changing a model rule produces a large
698 change in the results, then it suggests that the model component requires additional investigation and
699 development. In this section, we report on the results of an Effects Analysis to explore how one
700 modeling rule and one input parameter affect the results of the SBM.

Methods

702 As with the Alternatives Analysis, the Effects Analysis uses the relative change in the response
703 variables, but only includes one alternative. Alt06 was chosen because it consistently showed the largest
704 difference from existing conditions in the Alternatives Analysis. If the Effects Analysis shows a change
705 in the results for Alt06, then we might expect a smaller magnitude change for the other alternatives.

706 We focused the Effects Analysis on components of the model with the highest uncertainty and largest
707 potential impact on the Alternatives Analysis. In the next few sections, we will briefly describe the
708 model rule used in the analysis of alternatives, which is described in detail in the Model Documentation
709 above, and then we will describe in detail the other rules included in the Effects Analysis.

Rearing Rules

711 The default rearing rules are based on temperature, fish size, and run timing (see Floodplain
712 Rearing/Rearing Rules). The temperature rule is simply a critical date (June 1st) when temperatures in
713 the Yolo Bypass were likely to be too warm for floodplain rearing. The fish size rule is a threshold size
714 (120 mm) above which model fish do not engage in rearing behavior. The run timing rule triggers fish to
715 stop rearing and start migrating such that they will arrive at Chipps Island by the last date observed at
716 Chipps Island for each run. The run timing rule applies the same date across all years and is not sensitive
717 to changing hydrological conditions. Juvenile Chinook salmon are able to use changing hydrological
718 conditions on the floodplain to determine when to stop rearing and begin moving downstream again
719 (Moyle et al. 2007). In the Effects Analysis, we use changes in the total area inundated on the Yolo
720 Bypass as the proxy measure for cues that fish might use to make rearing decision and contrast the
721 inundation rule with the run timing rule.

722 The inundation rule requires two decisions: (1) how long of a time period over which to assess changes
723 in inundation and (2) how big of a change in inundation is required to change rearing behavior. We
724 provide a web tool for interested readers to explore the consequence of those decisions:
725 https://fishsciences.shinyapps.io/yolo-bypass-suitable-habitat/. We used juvenile salmonid catch timing
726 on the Yolo Bypass (Takata et al. 2017) to roughly guide our decisions about the change time period and
727 threshold change. In the Effects Analysis, we consider two time periods 30 and 60 days, but only one
728 threshold for each time period (±120 and ±60, respectively). The inundation change is calculated as the
729 slope between inundation on the current day and inundation 30 (or 60) days ago. Only those two time
730 points are used in the calculation of the slope. If the slope is above the upper threshold value, and

731   suitable habitat is available, then a rearing-eligible cohort will start or continue rearing. If the slope is
732   below the lower threshold value, then cohorts will stop rearing and continue migrating through the Canal
733   Complex. If the slope is between the upper and lower threshold values, then fish do not change their
734   current rearing status.

Rearing Survival

736   The default value of daily rearing survival is 0.99 based on an analysis (see
737   https://fishsciences.shinyapps.io/yolo-bypass-rearing-survival/) of floodplain growth and ocean survival
738   that suggested that 0.99 is an approximate minimum value of rearing survival to make rearing
739   worthwhile (i.e., growth benefits outweigh survival costs of rearing) across the range of fish sizes in the
740   model. In the Effects Analysis, we evaluated two additional levels of rearing survival: 0.97 and 0.95.
741   The levels are chosen to illustrate conditions where rearing is not beneficial for small fish (0.97) and not
742   beneficial for any fish (0.95) based on the supplementary analysis of rearing survival (see
743   https://fishsciences.shinyapps.io/yolo-bypass-rearing-survival/).

Results

745   We report results of the Effects Analysis for the same five metrics (juvenile survival, fork length, fork
746   length variation, entry timing variation, returning adults) described in the Alternatives Analysis. We also
747   include travel time, not as a fish benefits metric, but as a metric that provides additional information for
748   understanding the fish benefits metrics.

Juvenile Travel Time to Estuary Entry

750   Travel time is calculated as the mean travel time from Knights Landing to Chipps Island weighted by
751   the abundance of fish in the cohort. For fish migrating through the Yolo Bypass route, travel time also
752   includes time spent rearing. Travel times were longest at high rearing survival under the run timing
753   rearing rule, particularly for fall- and spring-run fish (Figure 13.). Fall- and spring-run fish enter the
754   model at the smallest size and have the latest run timing dates, and, thus, have the longest potential
755   rearing times under the run timing rule. If rearing survival is high, more of the fish that spent a long time
756   rearing on the floodplain make it to Chipps Island, which increases the mean travel time. The inundation
757   rearing rules produce shorter travel times under high rearing survival because small spring- and fall-run
758   fish are prompted to resume migration sooner than under the run timing rule. Under the lowest rearing
759   survival, travel times are slightly shorter for the run timing rule for fall- and spring-run fish because the
760   long rearing fish in the run timing rule do not survive to Chipps Island. The travel time patterns for fall-,
761   spring-, and winter-run fish generally do not hold for late-fall fish because many late-fall fish enter the
762   model above the 120 mm threshold and, thus do not rear on the floodplain.
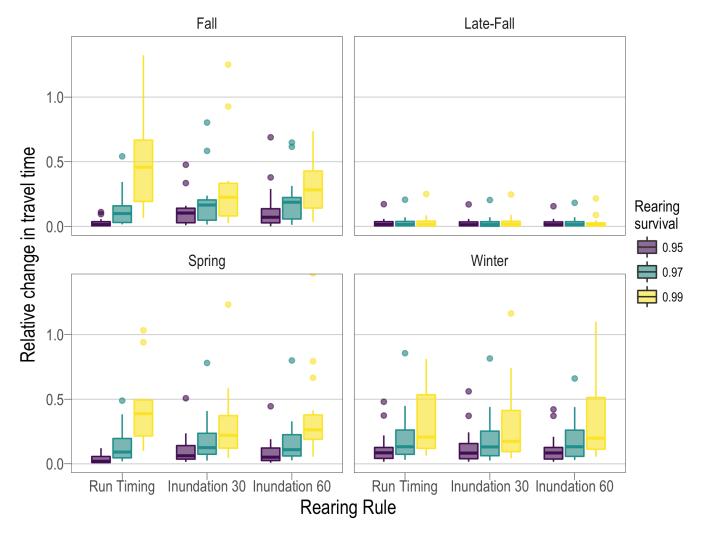
Figure 13. Relative change in mean travel time from Knights Landing to Chipps Island for 15 years under three rearing rule and three levels of rearing survival. The line near the center of the box is the median, the bottom and top of the box are the 25th and 75th percentiles, respectively, the whiskers show the min/max (unless there are outliers), and the points are outliers (+/- 1.5x interquartile from 75th and 25th percentile, respectively).

Juvenile Survival to Estuary Entry

Juvenile survival is calculated as the proportion of fish that survive from Knights Landing to Chipps Island. Because the Canal Complex route has lower migrating survival, and floodplain rearing incurs a survival cost, the increased entrainment of fish onto the Yolo Bypass via a notch in Fremont Weir reduces juvenile survival relative to existing conditions (Figure 14). Late-fall-run fish have the smallest relative change in juvenile survival because most late-fall-run fish enter the model above the size threshold (i.e., they do not rear and incur the cost of rearing).

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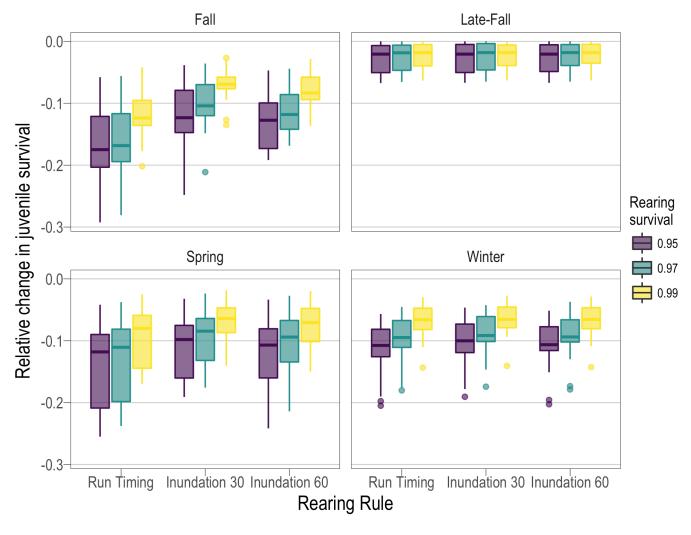
Figure 14. Relative change in juvenile survival from Knights Landing to Chipps Island for 15 years under three rearing rule and three levels of rearing survival. The line near the center of the box is the median, the bottom and top of the box are the 25th and 75th percentiles, respectively, the whiskers show the min/max (unless there are outliers), and the points are outliers (+/- 1.5x interquartile from 75th and 25th percentile, respectively).

Juvenile Fork Length at Estuary Entry

Fork length is calculated as the mean fork length of all cohorts that arrive at Chipps Island weighted by the abundance of fish in the cohort. The patterns in the effects analysis of fork length (Figure 15) resemble the patterns observed for travel time (Figure 13). The underlying mechanisms that create the patterns in travel time (see Juvenile Travel Time) are the same as for fork length.
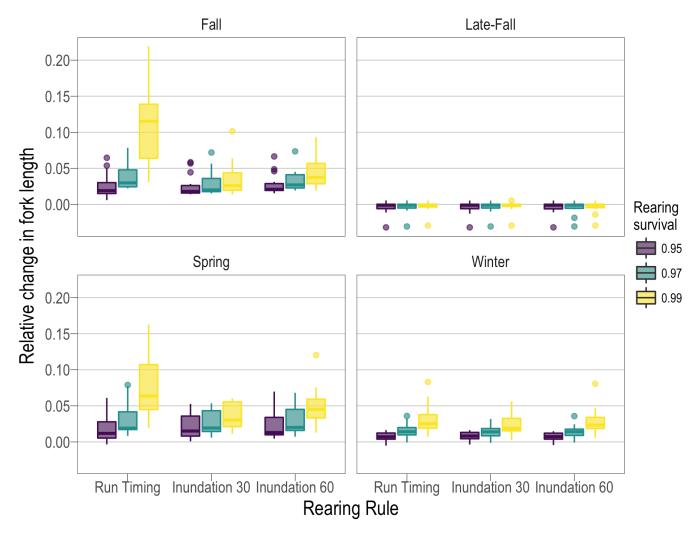
Figure 15. Relative change in mean fork length (mm) at Chipps Island for 15 years under three rearing rule and three levels of rearing survival. The line near the center of the box is the median, the bottom and top of the box are the 25th and 75th percentiles, respectively, the whiskers show the min/max (unless there are outliers), and the points are outliers (+/- 1.5x interquartile from 75th and 25th percentile, respectively).

Juvenile Fork Length Variation at Estuary Entry

Fork length variation is calculated as the coefficient of variation in fork length of all cohorts that arrive at Chipps Island weighted by the abundance of fish in the cohort. Across most effects, runs, and years, fork length variation is higher under the alternative than existing conditions (Figure 16). Late-fall-run fish show small relative change in fork length variation because most late-fall-run fish enter the model above the size threshold and do not rear on the floodplain. Relative change in fork length variation is one metric where you can see the difference between the effects of inundation window length; there is greater variation under the 60-day inundation window for fall- and spring-run. This is likely because fish rear longer under the 60-day rule and differential growth rates result in more variation at estuary entry.
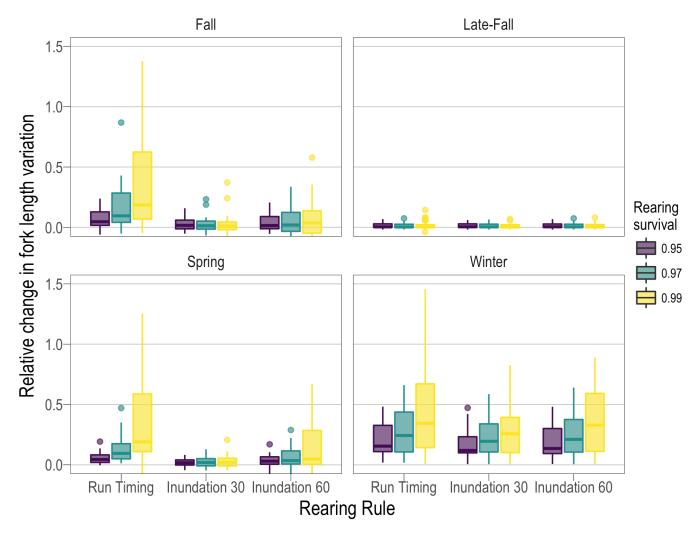
Figure 16. Relative change in coefficient of variation in fork length at Chipps Island for 15 years under three rearing rule and three levels of rearing survival. The line near the center of the box is the median, the bottom and top of the box are the 25th and 75th percentiles, respectively, the whiskers show the min/max (unless there are outliers), and the points are outliers (+/- 1.5x interquartile from 75th and 25th percentile, respectively). Note, the y-axis has been truncated to exclude some outliers. The non-truncated figure is available upon request.

Juvenile Timing Variation at Estuary Entry

Entry timing variation is calculated as the coefficient of variation in timing of all cohorts that arrive at Chipps Island weighted by the abundance of fish in the cohort. Timing is measured as day of water year when a cohort arrives at Chipps Island where October 1st is day one. For winter- and late-fall-run, there are only small effects of rearing rule and rearing survival on entry timing variation (Figure 17). For fall- and spring-run, under the run timing rearing rule, higher rearing survival yields more variation across years in entry timing variation.

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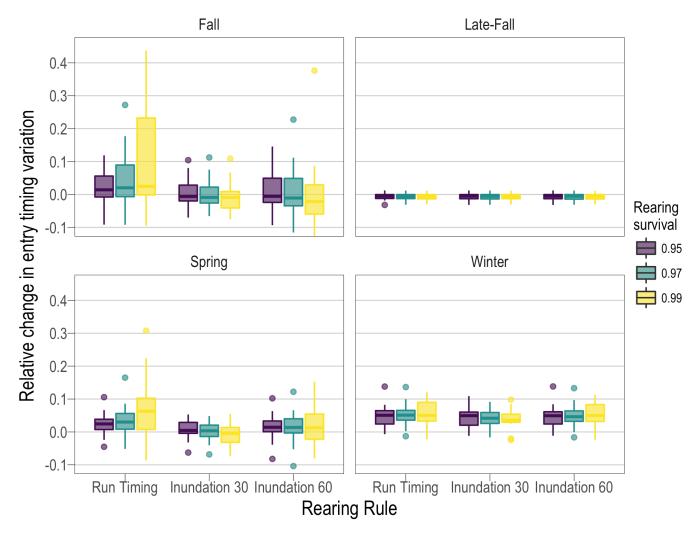
Figure 17. Relative change in coefficient of variation in estuary (Chipps Island) entry timing for 15 years under three rearing rule and three levels of rearing survival. The line near the center of the box is the median, the bottom and top of the box are the 25th and 75th percentiles, respectively, the whiskers show the min/max (unless there are outliers), and the points are outliers (+/- 1.5x interquartile from 75th and 25th percentile, respectively). Note, the y-axis has been truncated to exclude some outliers. The non-truncated figure is available upon request.

Returning Adults

The number of returning adults depends on both the number and size of fish that arrive at Chipps Island because the ocean survival relationship is a function of size. The returning adults metric shows the combined effect of the juvenile survival and fork length metrics. For all runs, except late-fall run, the potential benefits of increased floodplain access provided by the alternative only outweigh the costs of additional time spent rearing under the highest level of rearing survival but not in all years or under all rearing rules (Figure 18.). The effect of rearing survival on relative returning adults is strongest for fall- and spring-run fish under the run timing rule. Across all effects and years, late-full-run benefits from the presence of a notch in Fremont Weir, mostly because they enter the model at a large size, which carries benefits throughout the model (e.g., migration survival, growth, and ocean survival). Winter-run fish exhibit the smallest effect of rearing rule, other than late-fall run, presumably because they enter the model at a relatively large size and move through the system at a time of relatively high inundation, i.e., they are most likely triggered to stop rearing by growing to the size threshold (120 mm) than by the run timing or inundation rearing rules.
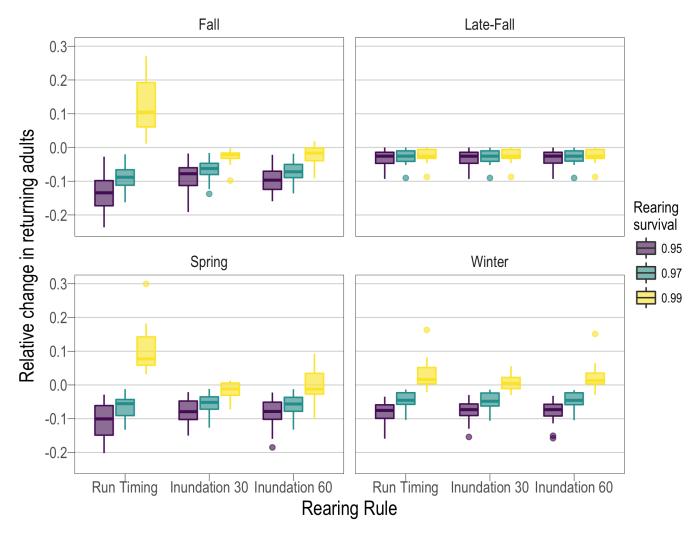
Figure 18. Relative change in number of returning adults for 15 years under three rearing rule and three levels of rearing survival. The line near the center of the box is the median, the bottom and top of the box are the 25th and 75th percentiles, respectively, the whiskers show the min/max (unless there are outliers), and the points are outliers (+/- 1.5x interquartile from 75th and 25th percentile, respectively).

Conclusions

We examined the effect of three rearing rules and three levels of rearing survival on the results produced by the SBM. We focus here on results of these model rules on fork length variation and returning adults. Fork length variation is highly correlated to entry timing variation and may reflect population resilience to changing ocean conditions from year to year. The number of returning adults measures the productivity of the population and incorporates the combined effects of juvenile growth and survival.

For all runs, except late-fall, rearing survival is the key factor in determining the benefit of Alt06; at a value of 0.95, rearing survival on the floodplain is too low to yield a benefit to implementing the Alt06 notch. Because Alt06 exhibited the biggest differences in the Alternatives Analysis, we might expect that the other notches (Alt01, Alt04, Alt04b, Alt05) would not yield a benefit at a rearing survival of 0.95 or 0.97.

There is an interactive effect of the rearing rule and rearing survival value. We suggest that both should be targets for additional study, but recognize the challenges in the design of such studies. For example,

851   acoustic telemetry studies can estimate survival from release at the top of the Yolo Bypass to arrival at
852   Chipps Island, but those studies are not able to partition survival into migrating and rearing components.
853   Furthermore, acoustic telemetry cannot yet accommodate fish smaller than about 74mm FL, missing the
854   ability to evaluate alternative effects on smaller juveniles. Using net pens to study fish on the floodplain
855   can provide estimates of rearing survival, but those estimates are probably lower bounds on actual
856   rearing survival because the pens constrain the juvenile salmons' ability to evade avian predators, find
857   more suitable habitat, or migrate volitionally.

858   While studies that directly inform modeling rules and parameters are ideal, it is also useful to design
859   studies that provide data to calibrate or validate the model. For example, median survival from Fremont
860   Weir to Chipps Island through the Yolo Bypass was less than 2% for spring- and fall-run under the run
861   timing rearing rule and rearing survival of 0.95. There are no studies of fall- and spring-run survival
862   through the Yolo Bypass, but it seems improbable that overall survival is so low for those runs, which
863   suggests that either 0.95 is too low of a value for rearing survival or the run timing rearing rule does not
864   adequately capture rearing behavior (or both).

865   The rearing rules examined in this Effects Analysis represent different modeling approaches. The run
866   timing rule limits rearing behavior by placing constraints on rearing that do not change from year to
867   year. The inundation rule allows fish to respond to changing conditions. Because the SBM is not an
868   optimality model, some combinations of the rearing rules and rearing survival potentially yield sub-
869   optimal behavior (e.g., if goal is to optimize probability of returning as an adult).

870   An earlier version of the SBM identified entrainment as the key factor in maximizing fish benefits from
871   a notch in the Fremont Weir. That version of the model was parameterized such that fish did not incur a
872   survival cost for rearing. Thus, more time spent rearing yielded the benefit of increased growth without
873   the cost of increased mortality. That earlier model also suggested that suitable habitat on the Yolo
874   Bypass, based on depth and velocity, was not often limiting. The combination of high rearing survival
875   and abundant suitable habitat meant that the limiting factor was entrainment onto the Yolo Bypass. If the
876   current version of the model is underestimating rearing survival, or implementing sub-optimal rearing
877   rules, then the importance of entrainment for fish benefits may be underestimated. As it is, addition of
878   rearing mortality to fish entrained on the Yolo Bypass. It is also important to note that while the effects
879   analysis shows a net decrease in juvenile survival across alternatives due to rearing mortality (Figure
880   14), the juvenile survival effects analysis does not incorporate the presumed survival benefits received
881   for having grown while rearing. These benefits are presumably captured by the effects analysis of
882   rearing rules on adult returns (Figure 18) and fork length variation (Figure 16), which do exhibit some
883   large net positive changes for all runs under Alternative 6.

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APPENDIX A: ALTERNATIVES ANALYSIS TABLES

Tables of Salmon Benefits Metrics

Table A-1. Juvenile survival from Knights Landing to Chipps Island under existing conditions (Exg) and five alternatives for notches in Fremont Weir.

Run	Water Year	Exg	Alt01	Alt04	Alt04b	Alt05	Alt06
Fall	1997	0.177	0.172	0.174	0.174	0.174	0.169
Fall	1998	0.562	0.535	0.547	0.550	0.544	0.520
Fall	1999	0.596	0.517	0.552	0.552	0.545	0.476
Fall	2000	0.620	0.566	0.578	0.578	0.575	0.534
Fall	2001	0.415	0.407	0.406	0.407	0.405	0.398
Fall	2002	0.225	0.216	0.218	0.218	0.216	0.206
Fall	2003	0.219	0.196	0.204	0.204	0.202	0.180
Fall	2004	0.213	0.199	0.202	0.202	0.201	0.190
Fall	2005	0.226	0.214	0.214	0.214	0.213	0.202
Fall	2006	0.505	0.471	0.484	0.484	0.480	0.438
Fall	2007	0.415	0.385	0.391	0.391	0.387	0.368
Fall	2008	0.415	0.383	0.387	0.387	0.385	0.364
Fall	2009	0.415	0.376	0.386	0.386	0.384	0.356
Fall	2010	0.414	0.384	0.399	0.399	0.397	0.360
Fall	2011	0.360	0.338	0.349	0.349	0.345	0.312
Late-Fall	1997	0.184	0.176	0.179	0.179	0.178	0.172
Late-Fall	1998	0.659	0.656	0.656	0.656	0.655	0.651
Late-Fall	1999	0.686	0.669	0.675	0.675	0.673	0.660
Late-Fall	2000	0.686	0.678	0.680	0.680	0.679	0.673
Late-Fall	2001	0.415	0.414	0.414	0.414	0.414	0.414
Late-Fall	2002	0.226	0.224	0.223	0.223	0.222	0.220
Late-Fall	2003	0.226	0.219	0.221	0.221	0.221	0.215
Late-Fall	2004	0.226	0.221	0.221	0.221	0.221	0.213
Late-Fall	2005	0.220	0.220	0.220	0.220	0.220	0.220
Late-Fall	2006	0.486	0.485	0.485	0.485	0.485	0.483
Late-Fall	2007	0.415	0.413	0.413	0.413	0.413	0.410
Late-Fall	2008	0.415	0.408	0.409	0.409	0.407	0.403
Late-Fall	2009	0.415	0.415	0.415	0.415	0.415	0.415
Late-Fall	2010	0.415	0.415	0.415	0.415	0.415	0.415
Late-Fall	2011	0.400	0.389	0.393	0.393	0.392	0.384
Spring	1997	0.187	0.167	0.175	0.175	0.173	0.157

Spring	1998	0.653	0.640	0.642	0.642	0.637	0.621
Spring	1999	0.678	0.611	0.639	0.639	0.634	0.570
Spring	2000	0.642	0.618	0.623	0.623	0.621	0.605
Spring	2001	0.415	0.410	0.410	0.411	0.409	0.405
Spring	2002	0.226	0.220	0.220	0.220	0.219	0.213
Spring	2003	0.224	0.202	0.207	0.207	0.206	0.186
Spring	2004	0.225	0.214	0.216	0.216	0.215	0.203
Spring	2005	0.226	0.216	0.218	0.218	0.217	0.208
Spring	2006	0.649	0.613	0.621	0.621	0.616	0.580
Spring	2007	0.415	0.398	0.401	0.401	0.398	0.385
Spring	2008	0.415	0.397	0.399	0.399	0.397	0.383
Spring	2009	0.415	0.402	0.405	0.405	0.404	0.395
Spring	2010	0.413	0.379	0.394	0.394	0.392	0.346
Spring	2011	0.367	0.342	0.352	0.353	0.349	0.319
Winter	1997	0.192	0.182	0.185	0.185	0.184	0.175
Winter	1998	0.671	0.660	0.659	0.659	0.658	0.644
Winter	1999	0.678	0.632	0.648	0.648	0.645	0.604
Winter	2000	0.642	0.617	0.623	0.623	0.622	0.600
Winter	2001	0.415	0.410	0.409	0.409	0.408	0.403
Winter	2002	0.226	0.220	0.221	0.221	0.220	0.215
Winter	2003	0.223	0.204	0.209	0.209	0.208	0.191
Winter	2004	0.225	0.217	0.218	0.218	0.217	0.207
Winter	2005	0.226	0.216	0.218	0.218	0.217	0.208
Winter	2006	0.657	0.633	0.636	0.636	0.634	0.608
Winter	2007	0.415	0.408	0.408	0.408	0.407	0.398
Winter	2008	0.415	0.404	0.405	0.405	0.403	0.395
Winter	2009	0.415	0.402	0.405	0.406	0.405	0.396
Winter	2010	0.415	0.402	0.409	0.409	0.407	0.389
Winter	2011	0.407	0.380	0.389	0.389	0.387	0.362

Table A-2. Mean fork length (mm) at Chipps Island under existing conditions (Exg) and five alternatives for notches in Fremont Weir.

Run	Water Year	Exg	Alt01	Alt04	Alt04b	Alt05	Alt06
Fall	1997	72.8	74.1	73.6	73.6	73.6	75.1
Fall	1998	52.4	54.6	53.6	53.4	53.9	56.0
Fall	1999	47.1	53.4	50.4	50.4	50.9	57.5
Fall	2000	43.1	46.6	45.7	45.7	45.9	48.9
Fall	2001	57.7	58.8	58.9	58.8	59.0	60.0
Fall	2002	52.6	53.9	53.5	53.5	53.8	55.5
Fall	2003	41.9	44.4	43.5	43.5	43.6	46.4
Fall	2004	47.7	49.4	49.0	49.0	49.2	50.8
Fall	2005	45.8	47.3	47.3	47.3	47.3	48.7
Fall	2006	53.6	57.0	55.7	55.7	56.1	60.9
Fall	2007	43.6	46.7	46.1	46.1	46.4	48.6
Fall	2008	41.2	44.3	43.9	43.9	44.2	46.5
Fall	2009	44.2	48.3	47.2	47.1	47.3	50.7
Fall	2010	55.3	59.3	57.3	57.3	57.6	63.1
Fall	2011	53.5	56.7	55.1	55.0	55.6	61.0
Late-Fall	1997	135.3	135.8	135.6	135.6	135.7	136.0
Late-Fall	1998	89.6	89.6	89.7	89.7	89.6	89.6
Late-Fall	1999	97.2	97.1	97.2	97.2	97.1	97.0
Late-Fall	2000	128.8	128.7	128.8	128.8	128.8	128.7
Late-Fall	2001	126.3	126.3	126.3	126.3	126.3	126.2
Late-Fall	2002	121.8	121.8	121.9	121.9	121.8	121.7
Late-Fall	2003	77.1	75.8	76.1	76.1	76.1	74.9
Late-Fall	2004	119.5	119.6	119.7	119.7	119.7	119.9
Late-Fall	2005	46.4	46.2	46.2	46.2	46.2	46.1
Late-Fall	2006	60.9	60.7	60.7	60.7	60.6	60.5
Late-Fall	2007	113.3	113.4	113.4	113.4	113.4	113.6
Late-Fall	2008	138.8	138.9	138.9	138.9	138.9	138.9
Late-Fall	2009	149.0	149.0	149.0	149.0	149.0	149.0
Late-Fall	2010	56.9	56.9	56.9	56.9	56.9	56.8
Late-Fall	2011	90.5	90.2	90.3	90.3	90.3	90.0
Spring	1997	52.1	55.6	54.2	54.2	54.6	57.8
Spring	1998	41.5	42.2	42.1	42.1	42.4	43.3
Spring	1999	52.5	57.4	55.3	55.3	55.6	61.0
Spring	2000	70.7	72.9	72.5	72.5	72.6	74.2

Spring	2001	70.1	70.8	70.8	70.7	70.9	71.5
Spring	2002	52.6	53.4	53.4	53.4	53.5	54.2
Spring	2003	46.8	49.6	48.9	48.9	48.9	51.7
Spring	2004	48.2	49.4	49.3	49.3	49.4	50.8
Spring	2005	58.8	60.4	60.1	60.1	60.2	61.6
Spring	2006	49.6	51.7	51.3	51.3	51.6	54.0
Spring	2007	55.6	57.5	57.2	57.2	57.5	59.1
Spring	2008	52.1	54.0	53.9	53.9	54.1	55.7
Spring	2009	72.9	74.8	74.4	74.3	74.5	75.8
Spring	2010	56.8	61.1	59.0	59.0	59.4	66.0
Spring	2011	65.4	69.6	67.8	67.7	68.4	74.1
Winter	1997	104.0	105.6	105.0	105.0	105.3	106.6
Winter	1998	76.4	77.1	77.3	77.3	77.4	78.3
Winter	1999	80.1	82.9	81.9	81.9	82.2	85.1
Winter	2000	103.4	104.8	104.5	104.5	104.5	105.8
Winter	2001	101.4	102.0	102.1	102.0	102.2	102.8
Winter	2002	76.4	76.7	76.8	76.8	76.8	77.0
Winter	2003	83.0	85.2	84.6	84.6	84.7	87.0
Winter	2004	76.2	76.9	76.9	76.9	77.0	78.1
Winter	2005	85.5	86.5	86.3	86.3	86.3	87.2
Winter	2006	71.7	73.4	73.2	73.2	73.4	75.3
Winter	2007	76.8	77.6	77.7	77.7	77.8	78.9
Winter	2008	93.2	94.5	94.5	94.5	94.6	95.7
Winter	2009	104.9	106.2	105.9	105.8	106.0	106.9
Winter	2010	98.4	99.1	98.8	98.8	98.9	99.8
Winter	2011	75.6	79.1	77.9	77.9	78.2	81.9

Table A-3. Coefficient of variation in fork length at Chipps Island under existing conditions (Exg) and five alternatives for notches in Fremont Weir.

Run	Water Year	Exg	Alt01	Alt04	Alt04b	Alt05	Alt06
Fall	1997	0.308	0.302	0.305	0.305	0.305	0.299
Fall	1998	0.472	0.493	0.484	0.479	0.486	0.503
Fall	1999	0.464	0.537	0.514	0.514	0.519	0.549
Fall	2000	0.415	0.512	0.497	0.496	0.501	0.545
Fall	2001	0.366	0.374	0.374	0.374	0.375	0.381
Fall	2002	0.386	0.408	0.403	0.403	0.407	0.426
Fall	2003	0.260	0.403	0.364	0.363	0.371	0.466
Fall	2004	0.348	0.397	0.387	0.387	0.392	0.424
Fall	2005	0.293	0.354	0.353	0.353	0.356	0.397
Fall	2006	0.547	0.556	0.554	0.554	0.555	0.556
Fall	2007	0.269	0.421	0.400	0.400	0.414	0.472
Fall	2008	0.129	0.384	0.367	0.367	0.378	0.461
Fall	2009	0.213	0.427	0.392	0.390	0.397	0.481
Fall	2010	0.357	0.399	0.383	0.382	0.385	0.416
Fall	2011	0.411	0.442	0.429	0.428	0.435	0.459
Late-Fall	1997	0.143	0.143	0.143	0.143	0.143	0.143
Late-Fall	1998	0.511	0.512	0.512	0.512	0.513	0.514
Late-Fall	1999	0.445	0.451	0.449	0.449	0.450	0.454
Late-Fall	2000	0.223	0.224	0.224	0.224	0.224	0.224
Late-Fall	2001	0.131	0.131	0.131	0.131	0.131	0.131
Late-Fall	2002	0.109	0.108	0.108	0.108	0.108	0.108
Late-Fall	2003	0.623	0.633	0.630	0.630	0.630	0.640
Late-Fall	2004	0.045	0.046	0.046	0.046	0.047	0.049
Late-Fall	2005	0.583	0.576	0.578	0.578	0.578	0.572
Late-Fall	2006	0.508	0.508	0.508	0.508	0.508	0.507
Late-Fall	2007	0.067	0.069	0.069	0.069	0.069	0.071
Late-Fall	2008	0.073	0.073	0.073	0.073	0.073	0.073
Late-Fall	2009	0.133	0.133	0.133	0.133	0.133	0.133
Late-Fall	2010	0.962	0.962	0.962	0.962	0.962	0.962
Late-Fall	2011	0.444	0.450	0.448	0.448	0.448	0.454
Spring	1997	0.458	0.495	0.482	0.482	0.486	0.506
Spring	1998	0.395	0.428	0.422	0.422	0.435	0.469
Spring	1999	0.381	0.438	0.420	0.420	0.424	0.452

Spring	2000	0.257	0.271	0.269	0.269	0.269	0.277
Spring	2001	0.193	0.208	0.208	0.207	0.211	0.221
Spring	2002	0.350	0.371	0.369	0.369	0.373	0.392
Spring	2003	0.303	0.403	0.381	0.381	0.385	0.450
Spring	2004	0.317	0.370	0.361	0.360	0.365	0.410
Spring	2005	0.327	0.348	0.345	0.345	0.346	0.362
Spring	2006	0.411	0.471	0.457	0.457	0.464	0.511
Spring	2007	0.250	0.324	0.312	0.312	0.322	0.360
Spring	2008	0.175	0.282	0.276	0.276	0.285	0.336
Spring	2009	0.102	0.161	0.150	0.147	0.152	0.181
Spring	2010	0.200	0.328	0.284	0.284	0.293	0.388
Spring	2011	0.432	0.437	0.438	0.437	0.439	0.430
Winter	1997	0.184	0.185	0.185	0.185	0.185	0.186
Winter	1998	0.220	0.231	0.232	0.231	0.233	0.244
Winter	1999	0.197	0.235	0.222	0.222	0.225	0.250
Winter	2000	0.124	0.133	0.131	0.131	0.131	0.138
Winter	2001	0.048	0.063	0.064	0.063	0.065	0.076
Winter	2002	0.192	0.207	0.204	0.204	0.206	0.220
Winter	2003	0.102	0.156	0.142	0.142	0.145	0.182
Winter	2004	0.119	0.151	0.147	0.147	0.150	0.183
Winter	2005	0.123	0.151	0.146	0.146	0.146	0.166
Winter	2006	0.210	0.244	0.239	0.239	0.242	0.272
Winter	2007	0.102	0.135	0.136	0.136	0.141	0.170
Winter	2008	0.058	0.092	0.090	0.090	0.093	0.110
Winter	2009	0.048	0.072	0.068	0.066	0.069	0.081
Winter	2010	0.225	0.234	0.230	0.230	0.231	0.245
Winter	2011	0.187	0.252	0.232	0.232	0.238	0.282

Table A-4. Coefficient of variation in estuary (Chipps Island) entry timing under existing conditions (Exg) and five alternatives for notches in Fremont Weir.

Run	Water Year	Exg	Alt01	Alt04	Alt04b	Alt05	Alt06
Fall	1997	0.205	0.194	0.199	0.199	0.198	0.185
Fall	1998	0.305	0.307	0.306	0.303	0.305	0.308
Fall	1999	0.278	0.288	0.285	0.285	0.286	0.285
Fall	2000	0.207	0.241	0.234	0.234	0.236	0.257
Fall	2001	0.250	0.251	0.251	0.251	0.251	0.250
Fall	2002	0.250	0.250	0.251	0.251	0.252	0.249
Fall	2003	0.219	0.249	0.239	0.239	0.241	0.267
Fall	2004	0.233	0.240	0.239	0.239	0.240	0.244
Fall	2005	0.235	0.239	0.241	0.241	0.241	0.245
Fall	2006	0.327	0.330	0.328	0.328	0.329	0.329
Fall	2007	0.183	0.215	0.209	0.209	0.213	0.228
Fall	2008	0.158	0.205	0.200	0.200	0.203	0.228
Fall	2009	0.094	0.153	0.141	0.140	0.143	0.173
Fall	2010	0.263	0.263	0.264	0.264	0.264	0.259
Fall	2011	0.351	0.341	0.349	0.348	0.348	0.320
Late-Fall	1997	0.298	0.298	0.298	0.298	0.298	0.298
Late-Fall	1998	0.524	0.521	0.521	0.521	0.521	0.517
Late-Fall	1999	0.473	0.468	0.469	0.469	0.469	0.465
Late-Fall	2000	0.340	0.342	0.341	0.341	0.342	0.343
Late-Fall	2001	0.260	0.260	0.260	0.260	0.260	0.260
Late-Fall	2002	0.177	0.176	0.176	0.176	0.176	0.176
Late-Fall	2003	0.421	0.414	0.415	0.415	0.415	0.408
Late-Fall	2004	0.124	0.124	0.124	0.124	0.124	0.124
Late-Fall	2005	0.220	0.218	0.218	0.218	0.218	0.217
Late-Fall	2006	0.323	0.321	0.321	0.321	0.320	0.319
Late-Fall	2007	0.212	0.212	0.213	0.213	0.213	0.214
Late-Fall	2008	0.147	0.146	0.146	0.146	0.146	0.146
Late-Fall	2009	0.501	0.501	0.501	0.501	0.501	0.501
Late-Fall	2010	0.294	0.294	0.294	0.294	0.294	0.294
Late-Fall	2011	0.605	0.599	0.600	0.600	0.600	0.596
Spring	1997	0.378	0.382	0.381	0.381	0.381	0.382
Spring	1998	0.378	0.389	0.386	0.386	0.392	0.404
Spring	1999	0.436	0.431	0.435	0.435	0.435	0.419
Spring	2000	0.200	0.196	0.197	0.197	0.197	0.193

Spring	2001	0.173	0.175	0.175	0.174	0.175	0.176
Spring	2002	0.386	0.392	0.391	0.390	0.392	0.398
Spring	2003	0.285	0.312	0.305	0.305	0.306	0.328
Spring	2004	0.352	0.365	0.362	0.362	0.363	0.374
Spring	2005	0.343	0.344	0.343	0.343	0.344	0.344
Spring	2006	0.393	0.413	0.406	0.406	0.409	0.429
Spring	2007	0.281	0.296	0.293	0.293	0.295	0.302
Spring	2008	0.182	0.207	0.205	0.205	0.207	0.223
Spring	2009	0.095	0.102	0.101	0.100	0.101	0.105
Spring	2010	0.168	0.199	0.187	0.186	0.189	0.220
Spring	2011	0.336	0.324	0.332	0.331	0.331	0.307
Winter	1997	0.355	0.350	0.351	0.351	0.350	0.347
Winter	1998	0.458	0.457	0.456	0.456	0.457	0.455
Winter	1999	0.415	0.427	0.421	0.421	0.422	0.429
Winter	2000	0.218	0.221	0.219	0.219	0.220	0.223
Winter	2001	0.158	0.160	0.161	0.160	0.161	0.163
Winter	2002	0.308	0.314	0.312	0.313	0.313	0.321
Winter	2003	0.193	0.207	0.202	0.202	0.203	0.216
Winter	2004	0.251	0.260	0.259	0.259	0.259	0.269
Winter	2005	0.262	0.272	0.269	0.269	0.270	0.277
Winter	2006	0.330	0.347	0.344	0.344	0.345	0.364
Winter	2007	0.221	0.229	0.228	0.228	0.230	0.238
Winter	2008	0.121	0.129	0.128	0.128	0.129	0.134
Winter	2009	0.169	0.175	0.173	0.173	0.174	0.178
Winter	2010	0.354	0.360	0.357	0.357	0.358	0.368
Winter	2011	0.338	0.361	0.351	0.351	0.354	0.377

Table A-5. Number of adult returners under existing conditions (Exg) and five alternatives for notches in Fremont Weir.

Run	Water Year	Exg	Alt01	Alt04	Alt04b	Alt05	Alt06
Fall	1997	143,742	144,680	144,412	144,297	144,523	145,488
Fall	1998	379,048	396,574	388,761	385,948	391,001	406,786
Fall	1999	170,935	195,690	184,862	184,848	186,850	208,120
Fall	2000	301,757	334,844	328,261	328,143	329,831	351,424
Fall	2001	280,499	286,800	287,180	287,089	287,969	293,515
Fall	2002	181,353	185,118	184,198	184,189	184,889	188,860
Fall	2003	198,993	211,952	208,020	207,869	208,588	219,830
Fall	2004	133,484	137,955	136,898	136,931	137,442	140,723
Fall	2005	78,117	80,915	80,891	80,890	81,004	83,365
Fall	2006	381,293	401,224	393,892	393,921	396,260	421,107
Fall	2007	136,860	155,337	152,036	152,003	154,179	165,527
Fall	2008	39,065	45,448	44,744	44,744	45,193	49,314
Fall	2009	34,818	41,186	39,649	39,568	39,836	44,326
Fall	2010	31,050	34,038	32,642	32,639	32,828	36,503
Fall	2011	89,360	96,260	92,935	92,732	94,139	104,183
Late-Fall	1997	3,634	3,528	3,569	3,569	3,549	3,467
Late-Fall	1998	23,368	23,303	23,327	23,327	23,290	23,220
Late-Fall	1999	223,044	218,800	220,466	220,466	219,787	216,793
Late-Fall	2000	138,849	137,195	137,570	137,570	137,434	136,203
Late-Fall	2001	60,039	59,881	59,876	59,876	59,863	59,714
Late-Fall	2002	48,414	47,749	47,711	47,711	47,583	46,842
Late-Fall	2003	61,203	57,913	58,660	58,660	58,525	55,865
Late-Fall	2004	22,507	22,091	22,096	22,096	22,074	21,480
Late-Fall	2005	6,759	6,646	6,674	6,674	6,667	6,586
Late-Fall	2006	26,839	26,625	26,631	26,631	26,609	26,385
Late-Fall	2007	52,278	52,206	52,187	52,187	52,184	52,078
Late-Fall	2008	81,012	79,707	79,821	79,821	79,617	78,812
Late-Fall	2009	86,388	86,388	86,388	86,388	86,388	86,388
Late-Fall	2010	17,320	17,302	17,316	17,316	17,298	17,275
Late-Fall	2011	24,203	23,666	23,861	23,861	23,803	23,433
Spring	1997	876	914	900	899	903	932
Spring	1998	1,157	1,188	1,183	1,183	1,195	1,234
Spring	1999	26,018	29,016	27,781	27,781	28,006	30,762
Spring	2000	9,692	10,051	9,981	9,978	10,000	10,244

Spring	2001	5,105	5,200	5,201	5,192	5,219	5,299
Spring	2002	4,641	4,714	4,712	4,711	4,722	4,788
Spring	2003	3,783	4,015	3,963	3,960	3,969	4,165
Spring	2004	2,660	2,742	2,730	2,729	2,736	2,821
Spring	2005	3,989	4,081	4,063	4,063	4,067	4,143
Spring	2006	14,137	15,195	14,949	14,948	15,101	16,163
Spring	2007	5,357	5,799	5,723	5,724	5,793	6,114
Spring	2008	4,031	4,385	4,357	4,357	4,399	4,658
Spring	2009	4,434	4,663	4,610	4,598	4,619	4,776
Spring	2010	1,687	1,947	1,832	1,831	1,853	2,193
Spring	2011	1,828	1,949	1,901	1,898	1,920	2,060
Winter	1997	832	821	825	825	825	814
Winter	1998	1,190	1,207	1,211	1,212	1,212	1,232
Winter	1999	4,654	4,878	4,803	4,803	4,822	5,026
Winter	2000	8,329	8,363	8,359	8,359	8,359	8,378
Winter	2001	2,028	2,043	2,044	2,043	2,046	2,061
Winter	2002	3,854	3,844	3,856	3,856	3,853	3,832
Winter	2003	3,869	3,898	3,892	3,892	3,891	3,916
Winter	2004	3,650	3,669	3,670	3,672	3,672	3,700
Winter	2005	4,475	4,461	4,462	4,462	4,461	4,451
Winter	2006	19,530	20,311	20,213	20,213	20,278	21,136
Winter	2007	14,268	14,607	14,623	14,623	14,685	15,121
Winter	2008	3,118	3,192	3,188	3,188	3,197	3,253
Winter	2009	4,639	4,692	4,680	4,676	4,682	4,717
Winter	2010	7,017	7,019	7,035	7,035	7,042	7,025
Winter	2011	1,315	1,441	1,397	1,397	1,410	1,529